Market Design

Peter Cramton

Professor of Economics
University of Maryland
University of Cologne
www.cramton.umd.edu

9 November 2017

With contributions from
Axel Ockenfels
University of Cologne

Market design

- Establishes rules of market interaction
- Economic engineering
  - Economics
  - Computer science
  - Engineering, operations research

Market design accomplishments

- Improve allocations
- Improve price information
- Mitigate market failures
  - Reduce risk
  - Enhance competition

Applications

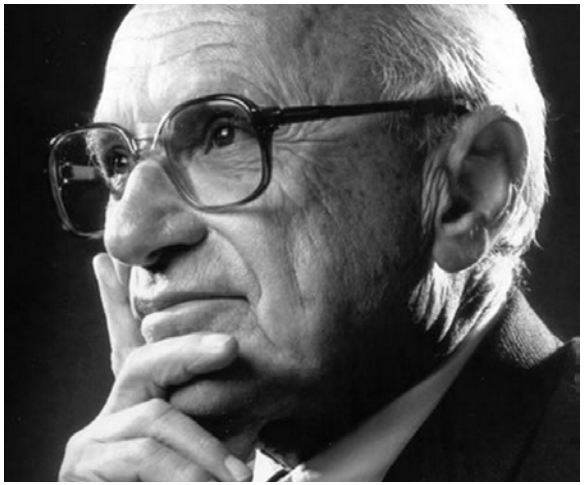
- *Matching (marriage, jobs, schools, kidneys, homes)*
- *Auctions*
  - *Electricity markets*
  - *Communication markets*
  - *Financial securities*
  - Transportation markets
  - Natural resource auctions
    (timber, oil, diamonds, pollution emissions)
  - Procurement

Innovation in a few words

- Electricity
  - Open access
  - Pay for performance
- Communications
  - Auction spectrum
  - Open access
- Transportation
  - Price congestion
- Climate policy
  - Price carbon
- Financial securities
  - Make time discrete

Resistance to market reforms is the norm:
Peter to regulator, "I can save you $10 billion."
Wall Street to regulator, "Hey, that's my $10 billion."
Distribution trumps efficiency

Milton Friedman



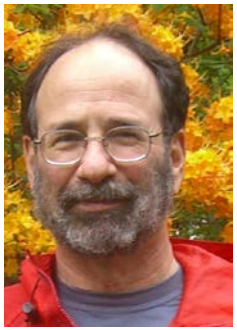
There is enormous inertia—a tyranny of the status quo—in private and especially governmental arrangements. Only a crisis—actual or perceived—produces real change. When that crisis occurs, the actions that are taken depend on the ideas that are lying around. That, I believe, is our basic function [as economists]: to develop alternatives to existing policies, to keep them alive and available until the politically impossible becomes politically inevitable.

What is economic engineering?

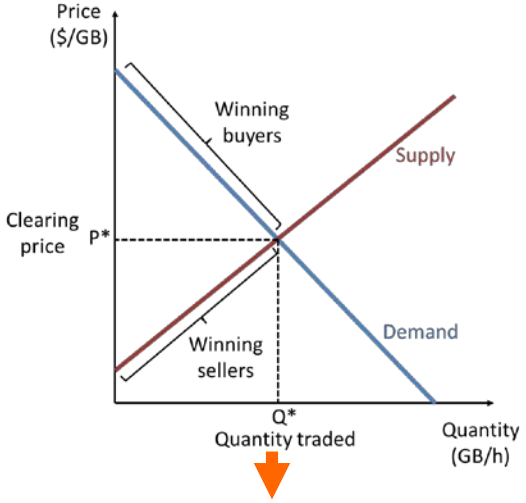
Economic engineering…

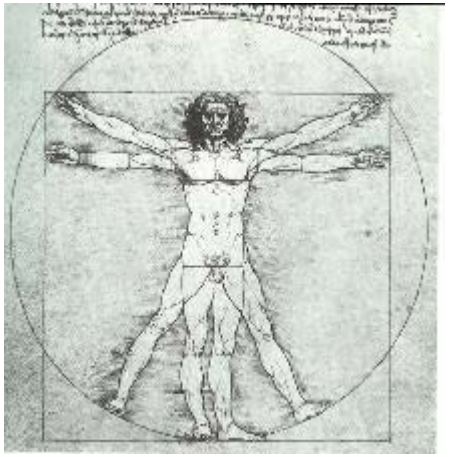
science of designing institutions and mechanisms that align individual incentives and behavior with the underlying goals

The Economist as Engineer
(Roth 2002)

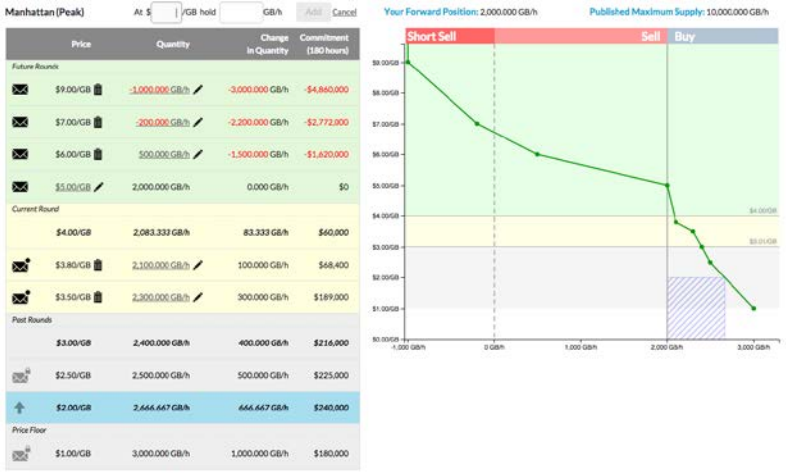


- Understand how markets work in enough detail so we can fix them when they're broken
- Build an engineering-oriented economics literature
  - Otherwise, the practical problems of design will be relegated to the arena of "just consulting" and we will fail to benefit from the accumulation of knowledge which is so evident in other kinds of engineering
- See
  - web.stanford.edu/~alroth
  - marketdesigner.blogspot.com





- Useful to distinguish two kinds of complexities
  - Institutional detail
  - Behavior



Economic engineering

- Identifies behavioral and institutional complexities that are relevant for a broader range of ‘real-world’ contexts
- Develops mechanisms, models and methods that can be proven to be robust against such complexities

Roth (2010) on why experiments are useful in market design

- Experiments are a natural part of market design, not least because to run an experiment, an experimenter must specify how transactions are carried out, and so experimenters are of necessity engaged in market design in the laboratory

- Experiments can serve multiple purposes in the design of markets outside of the lab
  - Scientific use of experiments to test hypotheses
  - Testbeds to get a first look at market designs that may not yet exist outside of the laboratory (Plott 1987)
  - Demonstrations and proofs of concept

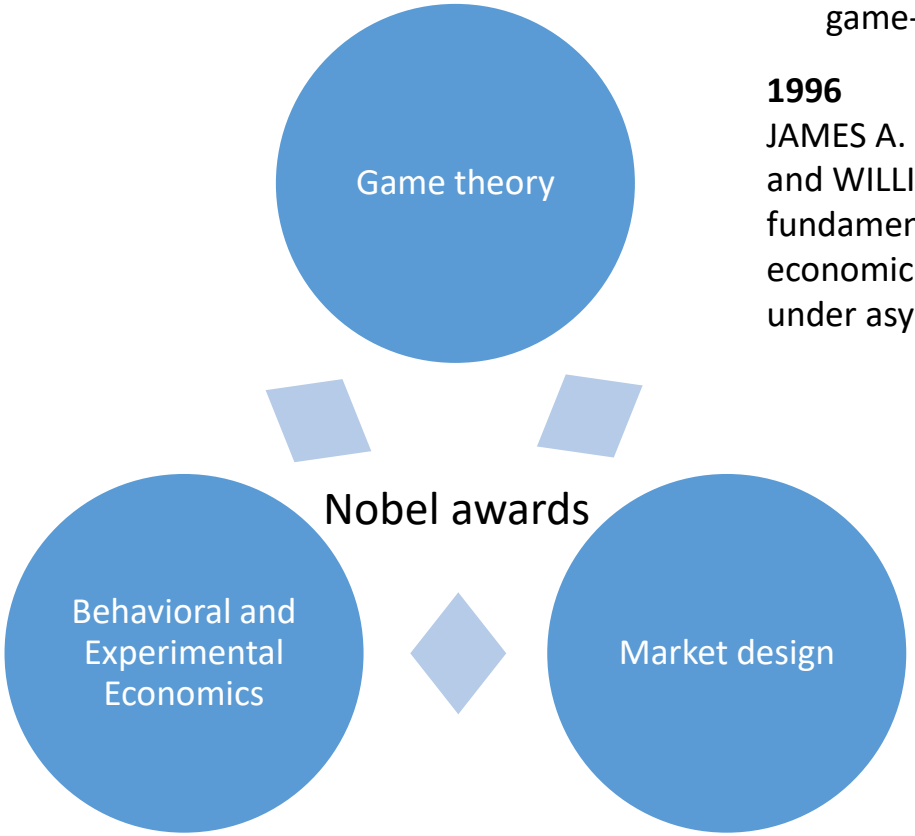
1994
JOHN C. HARSANYI ,
JOHN F. NASH and
REINHARD SELTEN for their pioneering analysis of equilibria in the theory of non-cooperative games

2001
GEORGE A. AKERLOF, A. MICHAEL SPENCE, and JOSEPH E. STIGLITZ, for their analyses of markets with asymmetric information

2005
ROBERT J.AUMANN and
THOMAS C. SCHELLING for having enhanced our understanding of conflict and cooperation through game-theory analysis

2002
VERNON L. SMITH for having established laboratory experiments as a tool in empirical economic analysis, especially in the study of alternative market mechanisms, and

DANIEL KAHNEMAN for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty



1996
JAMES A. MIRRLEES
and WILLIAM VICKREY for their fundamental contributions to the economic theory of incentives under asymmetric information

2007
LEONID HURWICZ, ERIC S. MASKIN, and ROGER B. MYERSON for having laid the foundations of mechanism design theory

2014
JEAN TIROLE for his analysis of market power and regulation

1978
HERBERT A. SIMON for his pioneering research into the decision-making process within economic organizations

2009
ELINOR OSTROM for her analysis of economic governance, especially the commons

2012
ALVIN E. ROTH and LLOYD SHAPLEY for the theory of stable allocations and the practice of market design

Objectives

- Efficiency
- Simplicity
- Transparency
- Fairness

It is good to keep these goals in mind whenever designing a market

Matching

One-sided matching

- Each of *n* agents owns house and has strict preferences over all houses
- Can the agents benefit from swapping?

Top trading cycles

- Each owner *i* points to her most preferred house (possibly *i*‘s own
- Each house points back to its owner
- Creates directed graph; identify cycles
  - Finite: cycles exist
  - Strict preference: each owner is in at most one cycle
- Give each owner in a cycle the house she points to and remove her from the market
- If unmatched owners/houses remain, iterate

Properties of top trading cycles

- Top-trading-cycle outcome is a core allocation
  - No subset of owners can make its members better off by an alternative assignment within the subset
- Top-trading-cycle outcome is unique
- Top-trading-cycle algorithm is strategy proof
  - No agent can benefit from lying about her preferences

Example

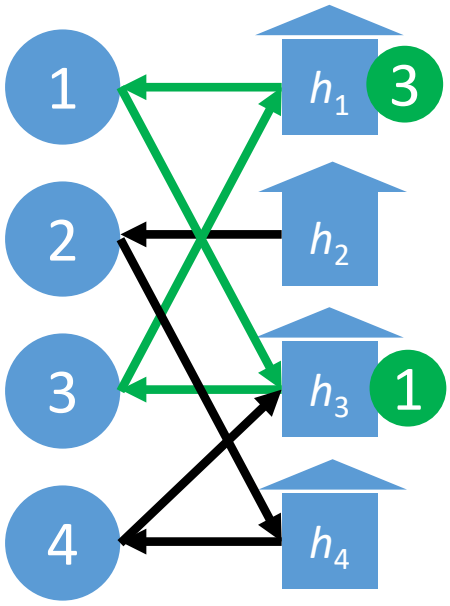
Owner's ranking from best to worst

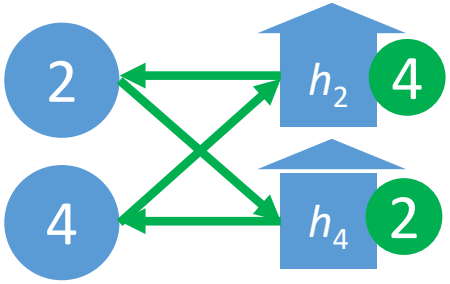
1: (h_3, h_2, h_4, h_1)

2: (h_4, h_1, h_2, h_2)

3: (h_1, h_4, h_3, h_3)

4: (h_3, h_2, h_1, h_4)

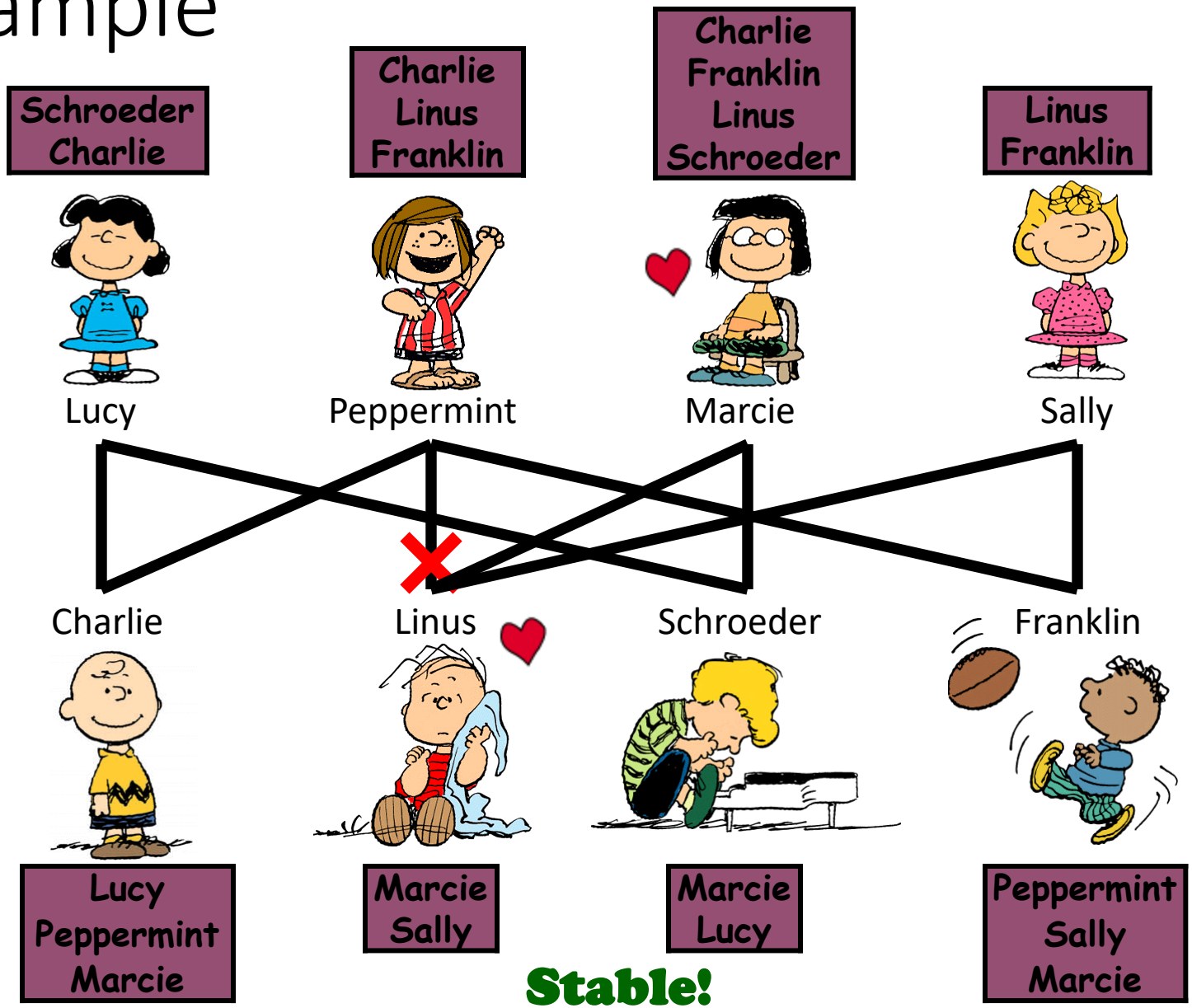




Two-sided matching

- Consider a set of *n* women and *n* men
- Each person has an ordered list of some members of the opposite sex as his or her *preference list*
- Let μ be a matching between women and men
- A pair *(m, w)* is a *blocking pair* if both *m* and *w* prefer being together to their assignments under μ. Also, *(x, x)* is a blocking pair, if *x* prefers being single to his/her assignment under μ
- A matching is *stable* if it does not have any blocking pair

Example


Schroeder
Charlie
Charlie
Linus
Franklin
Charlie
Franklin
Linus
Schroeder
Linus
Franklin
Lucy
Peppermint
Marcie
Sally
Charlie
Linus
Schroeder
Franklin
Lucy
Peppermint
Marcie
Marcie
Sally
Marcie
Lucy
Peppermint
Sally
Marcie
Stable!

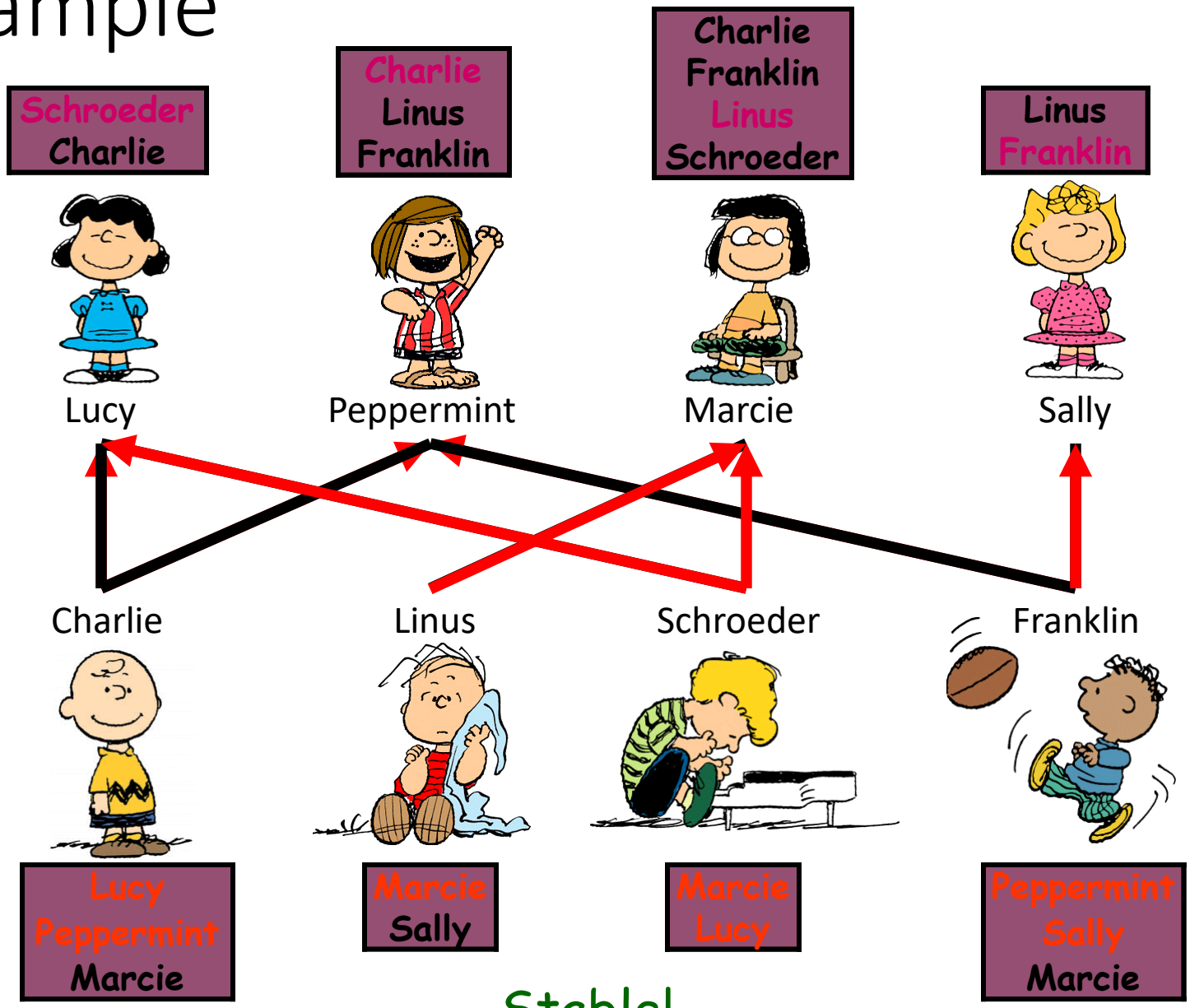
Deferred Acceptance Algorithms

(Gale and Shapley, 1962)

- In each iteration, an unmarried man proposes to the first woman on his list that he hasn't proposed to yet
- A woman who receives a proposal that she prefers to her current assignment accepts it and rejects her current assignment

This is called the men-proposing algorithm

Example



Stable!

Classical Results

- **Theorem 1.** The order of proposals does not affect the stable matching produced by the men-proposing algorithm

- **Theorem 2.** The matching produced by the men-proposing algorithm is the *best* stable matching for men and the *worst* stable matching for women

  This matching is called the *men-optimal* matching

- **Theorem 3.** In all stable matchings, the set of people who remain single is the same

Applications of stable matching

- Stable marriage algorithm has applications in the design of centralized two-sided markets
  - National Residency Matching Program (NRMP) since 1950's
  - Dental residencies and medical specialties in the US, Canada, and parts of the UK
  - National university entrance exam in Iran
  - Placement of Canadian lawyers in Ontario and Alberta
  - Sorority rush
  - Matching of new reform rabbis to their first congregation
  - Assignment of students to high-schools in NYC
  - …

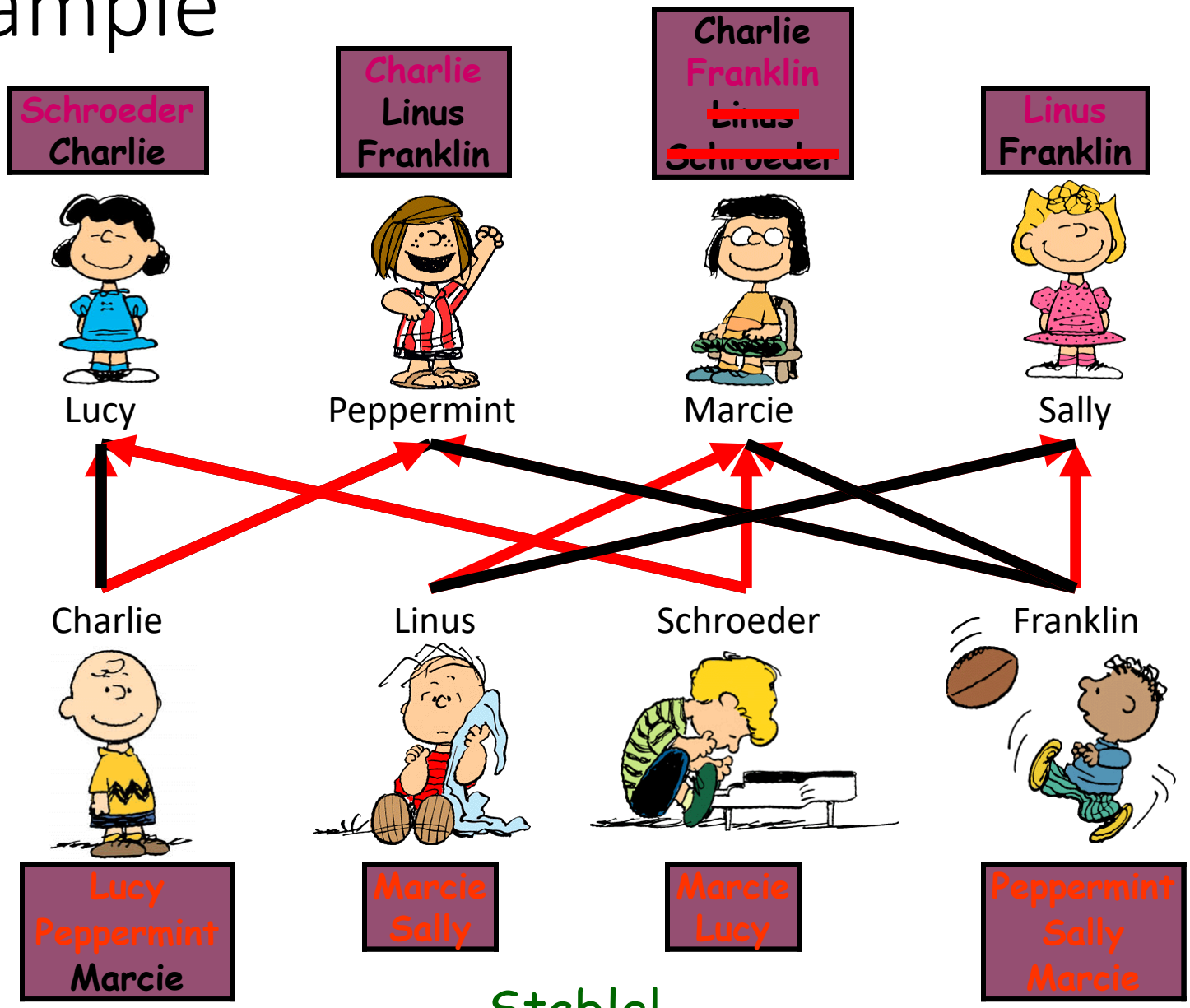
Incentive Compatibility

- Question: Do participants have an incentive to announce their real preference lists?

- Answer: No!

  In the men-proposing algorithm, sometimes women have an incentive to be dishonest about their preferences

Example



Stable!

Incentive Compatibility

- Next Question: Is there any truthful mechanism for the stable matching problem?

- Answer: No!

  Roth (1982) proved that there is no mechanism for the stable marriage problem in which truth-telling is the dominant strategy for *both* men and women

Applications

Electricity market design

Climate policy

Spectrum auction design

Future of mobile communications

Future of transportation

Future of financial markets

Electricity

Goals of electricity markets

- Short-run efficiency
  - Least-cost operation of existing resources
- Long-run efficiency
  - Right quantity and mix of resources

Key idea: open access

Challenges of electricity markets

- Must balance supply and demand *at every instant*
- Physical constraints of network
- Absence of demand response
- Climate policy

Three Markets

- Short term (5 to 60 minutes)
  - Spot energy market
- Medium term (1 month to 3 years)
  - Bilateral contracts
  - Forward energy market
- Long term (4 to 20 years)
  - Capacity market (thermal system)
  - Firm energy market (hydro system)
- Address risk, market power, and investment

Long-term market:
Buy enough in advance

Product

- What is load buying?
  - Energy during scarcity period (capacity)
- Enhance substitution
  - Technology neutral where possible
  - Separate zones only as needed in response to binding constraints
- Long-term commitment for new resources to reduce risk

Pay for Performance

- Strong performance incentives
  - Obligation to supply during scarcity events
    - Deviations settled at price > $5000/MWh
    - Penalties for underperformance
    - Rewards for overperformance
- Tend to be too weak in practice, leading to
  - Contract defaults
  - Unreliable resources
- But not in best markets: ISO New England, PJM

Global Carbon Pricing

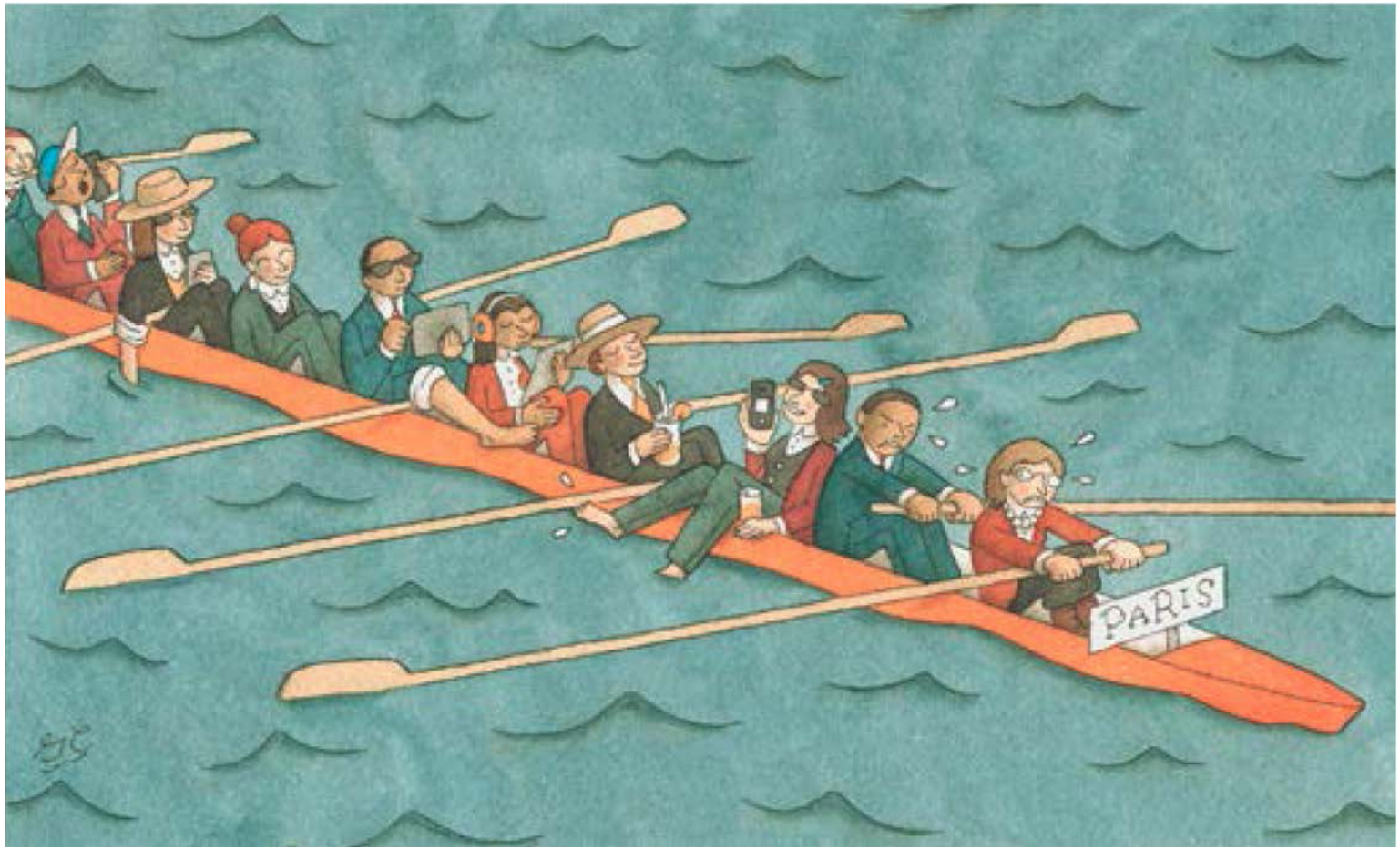
The Path to Climate Cooperation

edited by Peter Cramton, David JC MacKay, Axel Ockenfels, and Steven Stoft

Contributors

Richard N. Cooper
Peter Cramton
Ottmar Edenhofer
Christian Gollier
Éloi Laurent
David JC MacKay
William Nordhaus
Axel Ockenfels
Ian Parry
Joseph E. Stiglitz
Steven Stoft
Jean Tirole
Martin L. Weitzman

Climate change is a cooperation problem



Narrow self-interest?

IPCC (2014): "*International cooperation is necessary to significantly mitigate climate change because of the global nature of the problem*" … but:

Christine Figueres (2015): "*Frankly, none of them are doing it [agreeing to their pledges] to save the planet. Let us be very clear. They're doing it for what I think is a much more powerful political driving force, which is for the benefit of their own economy*"

Nicholas Stern (2015): "*most of what is necessary for emissions reductions over the next two decades is in the self-interest of the individual nations*"

Fergus Green (2015): "*the default assumption in social science scholarship should be that actions to reduce emissions are nationally net-beneficial*"

Narrow self-interest?

Limited carbon supply?

- Carbon supply >> Carbon budget at 2°C

Technological miracle?

- Very risky bet

Addressing local pollution?

- Global and domestic damages are additive

No need for an agreement to act in self-interest

Can cooperation be designed?

Reciprocity!

Virtually all cooperation research agrees that reciprocity is the key to cooperation

Nations exist mainly to achieve cooperation on public goods through enforced reciprocity

Reciprocity can sometimes be designed, even absent a central authority

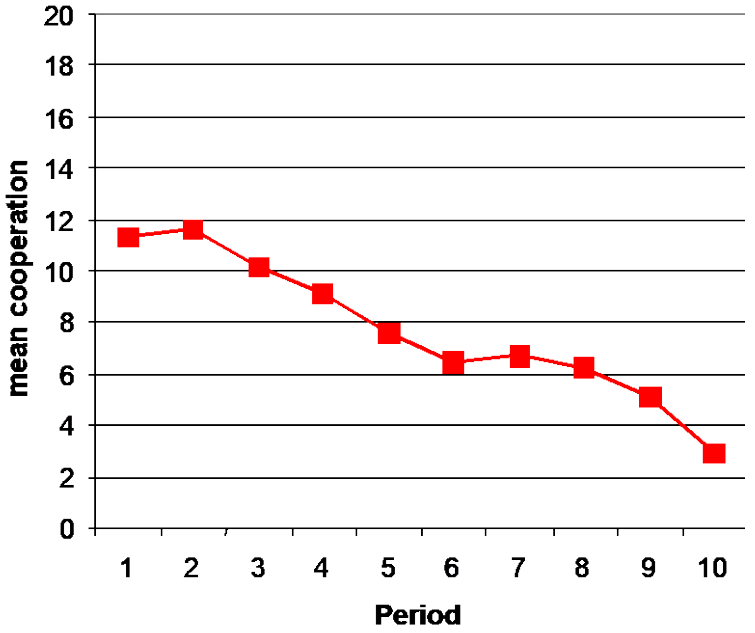
ELINOR OSTROM
2009 Nobel Laureate
in Economic Sciences
Nobel medal © ® The Nobel Foundation

Individual commitments cannot promote cooperation

- 10 players; individual endowment = $10
- Each $ pledged will be doubled and distributed evenly to all players
- Result: *Zero* cooperation, all pledge $0

Dynamics of individual commitments: "Upward spiral of ambition"?

- Japan, Russia, Canada, and New Zealand left the Kyoto agreement
- Ostrom (2010), based on hundreds of field studies: insufficient reciprocity leads to a "*downward cascade*"
- Supported by theory and laboratory experiments



"I will if you will" promotes cooperation

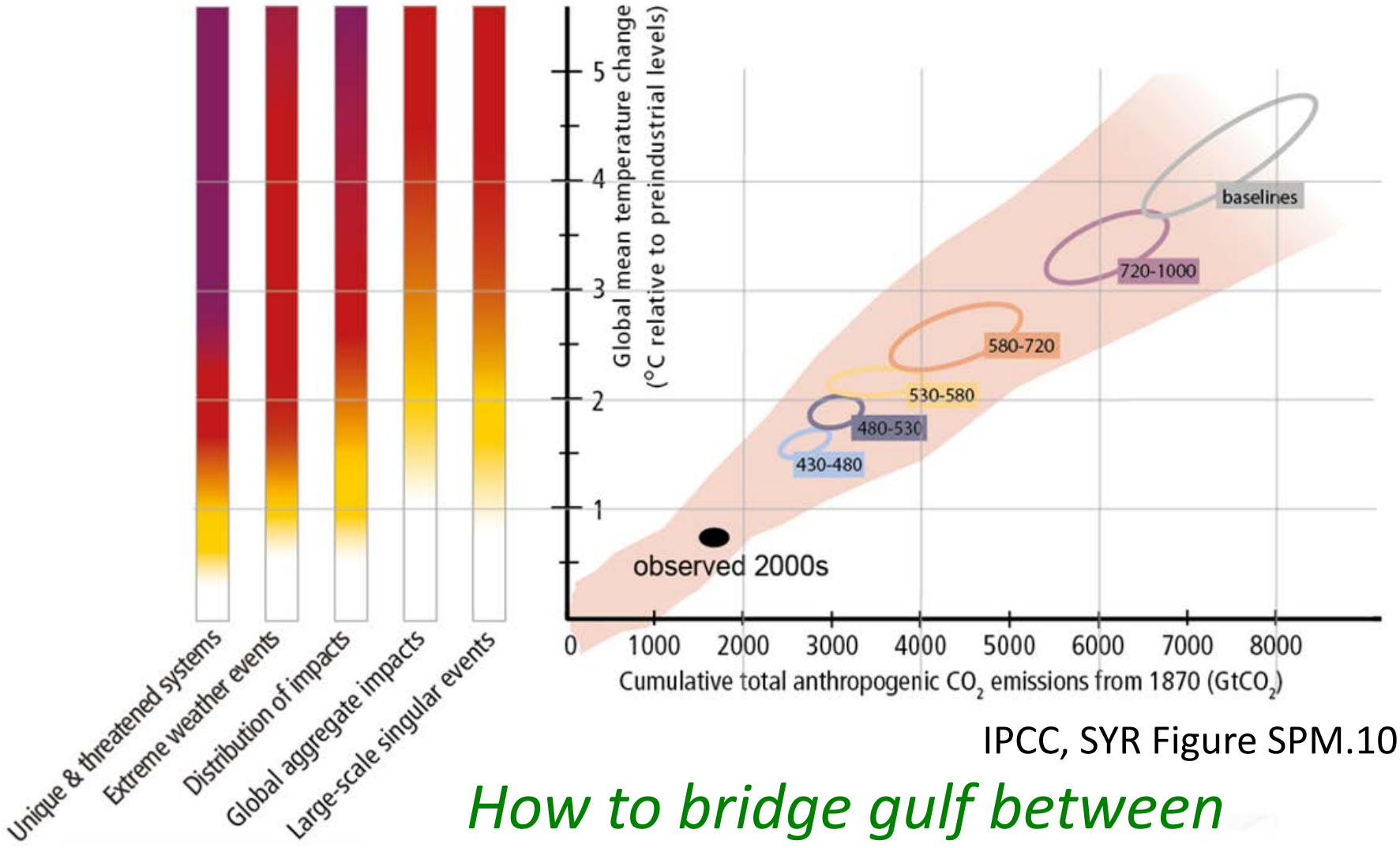
- 10 players; Individual endowment = $10
- Each $ pledged will be doubled and distributed evenly to all players
- *Pledge is commitment to reciprocally match the minimum pledge of others*
- Result: *Full* cooperation, all pledge $10

Reciprocal common commitment in climate negotiations

SECRETARIE EXECUTIVE CCNUCC
PRESIDENT

Consensus Aspiration: 2°C goal

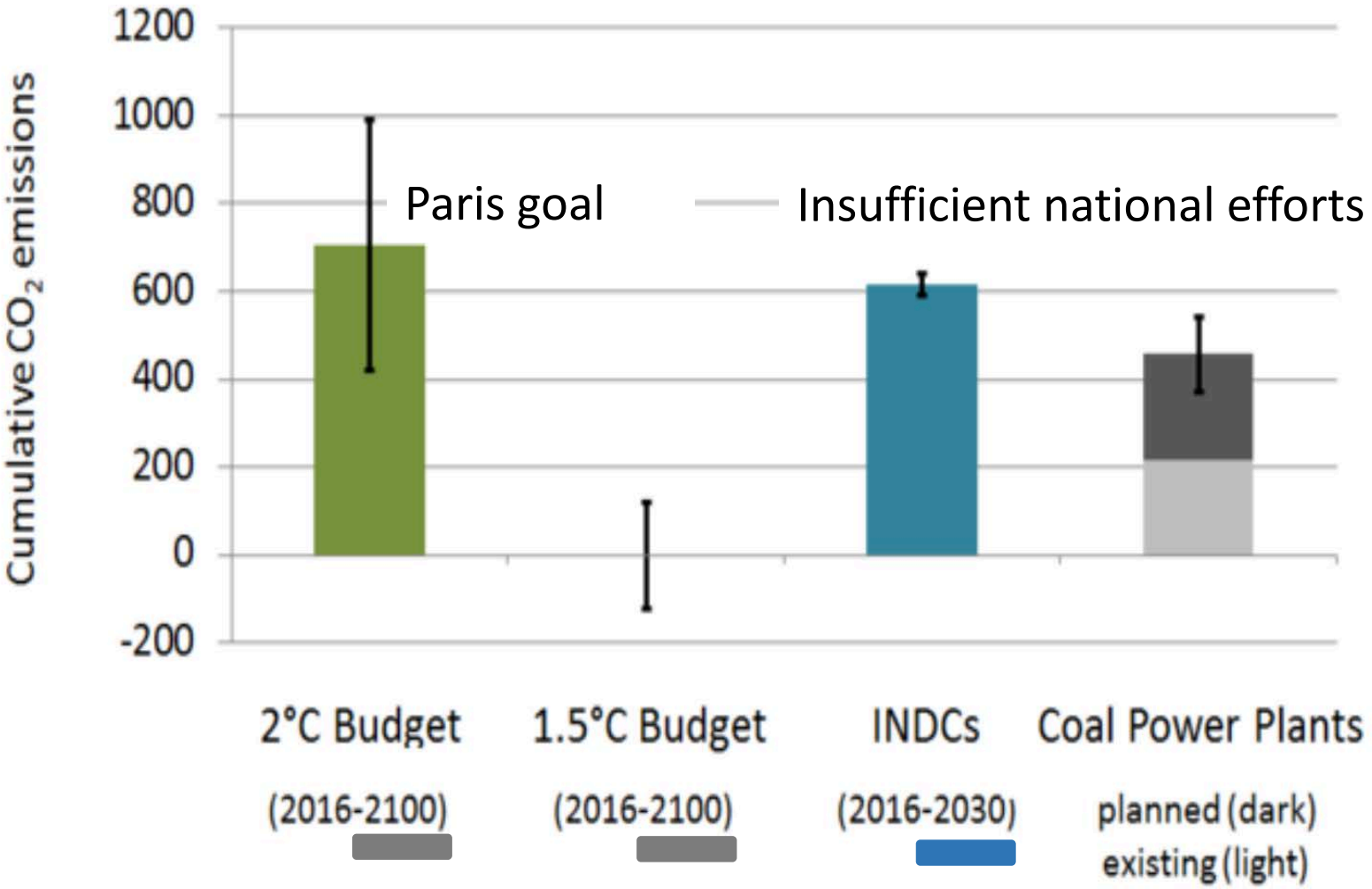
1.5°



IPCC, SYR Figure SPM.10

How to bridge gulf between goal and intentions?

Intended Nationally Determined Contributions fall short



Edenhofer et al. 2016

Global carbon price

- Direct
- Efficient
- Transparent
- *Promotes international cooperation*

Price is focal
common commitment

(and Kyoto proved quantity is not)

Consensus that price should be uniform reduces dimensionality problem:

$$P_{country} = P_{global}$$

(No such consensus exists for quantity commitment)

Consistent with tax or cap & trade (flexible at country level)

Direct, efficient, common intensity of effort

Price commitment reduces risk

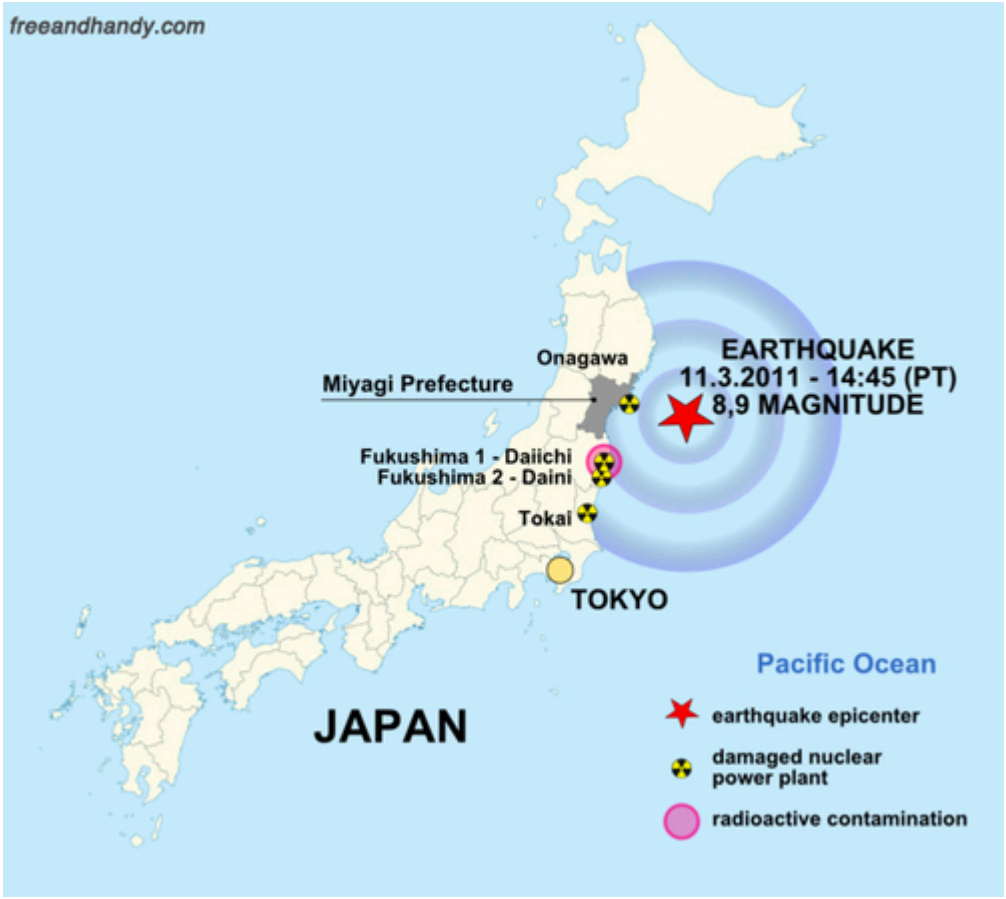
(compared to quantity commitment)

Stochastic shocks and other uncertainties destabilize cooperation, both in theory and empirics (e.g., Ambrus and Greiner 2012)

With carbon pricing, countries keep carbon revenues, which mitigates the risk of needing to buy carbon credits

Otherwise, huge windfall gains and losses possible

Price commitment reduces risk



- Quantity

Japan → $ → Rest of World

- Price

Japan ⇄ $ Rest of World

Asymmetries

Asymmetries hamper cooperation

- Establish coalition of the willing, omitting some
- Last resort enforcement with trade sanctions

Use Green Fund to maximize abatement

Cramton and Stoft 2012; Cramton et al. 2015a, Kornek, Edenhofer 2015; Roolfs et al. 2015

As before, reduce dimensionality

- Carbon price = intensity of cooperation
- “Generosity parameter” = intensity of Green Fund

National solution: carbon dividends

THE CONSENSUS CLIMATE SOLUTION

The Founding Members of the Climate Leadership Council believe that America needs a consensus climate solution that bridges partisan divides, strengthens our economy and protects our shared environment.

The Council's carbon dividends solution embodies the conservative principles of free markets and limited government. It also offers an equitable, popular and politically-viable way forward, paving the way for a much-needed bipartisan climate breakthrough.

Our carbon dividends program is based on four interdependent pillars:

1. A gradually rising and revenue-neutral carbon tax;
2. Carbon dividend payments to all Americans, funded by 100% of the revenue;
3. The rollback of carbon regulations that are no longer necessary; and
4. Border carbon adjustments to level the playing field and promote American competitiveness.

This plan would achieve significantly greater emissions reductions than all current and prior climate regulations, while helping America's businesses and workers get ahead. In fact, the bottom 70% of Americans would be financially better off.

Our carbon dividends solution is: Pro-Environment, Pro-Growth, Pro-Jobs, Pro-Competitiveness, Pro-Business and Pro-National Security.

Working with a range of constituencies, the Climate Leadership Council will develop and promote a consensus climate solution based on these pillars.

WSJ ad, 20 June 2017

Corporate Founding Members

NGO Founding Members

Individual Founding Members

Michael Bloomberg
Steven Chu
Ray Dalio
Martin Feldstein
Ted Halstead

Stephen Hawking
Vinod Khosla
N. Gregory Mankiw
Gregory Page
Laurene Powell Jobs

Thomas Stephenson
Lawrence Summers
Ratan Tata
Rob Walton

Distinguished Co-Authors

James A. Baker, III

George P. Shultz

WSJ ad, 20 June 2017

Conclusion

Cooperation can be engineered

Key to a strong climate treaty

- “I will if you will” (common commitment)
- Simplify: two parameters
  - Carbon price (common intensity of effort)
  - Green fund intensity (addresses asymmetries)

Price Carbon

I will if you will

Spectrum

Spectrum auctions

- Many items, heterogeneous but similar
- Competing technologies and business plans
- Complex structure of substitutes and complements

- Government objective: Efficiency
  - Make best use of scarce spectrum
  - *Address competition issues in downstream market*

Key design issues

- Establish term to promote investment
- Enhance substitution
  - Product design
  - Auction design
- Encourage price discovery
  - Dynamic price process to focus valuation efforts
- Encourage truthful bidding
  - Pricing rule
  - Activity rule

Simultaneous ascending auction

Prepare

Italy 4G Auction, September 2010
470 rounds, 22 days, €3.95B

- *Auction conducted on-site with pen and paper*
- *Auction procedures failed in first day*
- *No activity rule*

Thailand 3G Auction, October 2012

- 3 incumbents bid
- 3 nearly identical licenses
- Auction ends at reserve price + 2.8%

Conflict and cooperation in Germany's spectrum auctions

In Germany (1999) 10 spectrum blocks were simultaneously sold:

- New bid for a particular block must exceed prior bid by at least 10 percent
- Auction ends when no bidder is willing to bid higher on any block

What happened?

The auction begins …

	1	2	3	4	5	6	7	8	9	10
1										
2										
3										

The “offer” of Mannesmann (=M)

	1	2	3	4	5	6	7	8	9	10
1	36.4 M	36.4 M	36.4 M	36.4 M	36.4 M	40 M	40 M	40 M	40 M	56 M
2										
3										

T-Mobile (=T) “accepted”

	1	2	3	4	5	6	7	8	9	10
1	36.4 M	36.4 M	36.4 M	36.4 M	36.4 M	40 M	40 M	40 M	40 M	56 M
2	40 T	40 T	40 T	40 T	40 T	-	-	-	-	-
3										

Perfect cooperation

	1	2	3	4	5	6	7	8	9	10
1	36.4 M	36.4 M	36.4 M	36.4 M	36.4 M	40 M	40 M	40 M	40 M	56 M
2	40 T	40 T	40 T	40 T	40 T	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-

Combinatorial Clock Auction

Combinatorial clock auction

- Auctioneer names prices;
  bidder names package
  - Price increased if excess demand
  - Process repeated until no excess demand
- Supplementary bids
  - Improve clock bids
  - Bid on other relevant packages
- Optimization to determine assignment/prices

- No exposure problem (package auction)
- Second pricing to encourage truthful bidding
- Activity rule to promote price discovery

Pricing rule

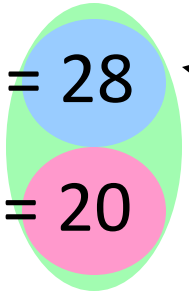
Bidder-optimal core pricing

- Minimize payments subject to core constraints
- Core = assignment and payments
  such that
  - Efficient: Value maximizing assignment
  - Unblocked: No subset of bidders offered seller a better deal

Optimization

- Core point that minimizes payments readily calculated
  - Solve Winner Determination Problem
  - Find Vickrey prices
  - Constraint generation method (Day and Raghavan 2007)
    - Find most violated core constraint and add it
    - Continue until no violation
- Tie-breaking rule for prices is important
  - Minimize distance from Vickrey prices

5 bidder example with bids on {A,B}



- $b_1\{A\} = 28$
- $b_2\{B\} = 20$

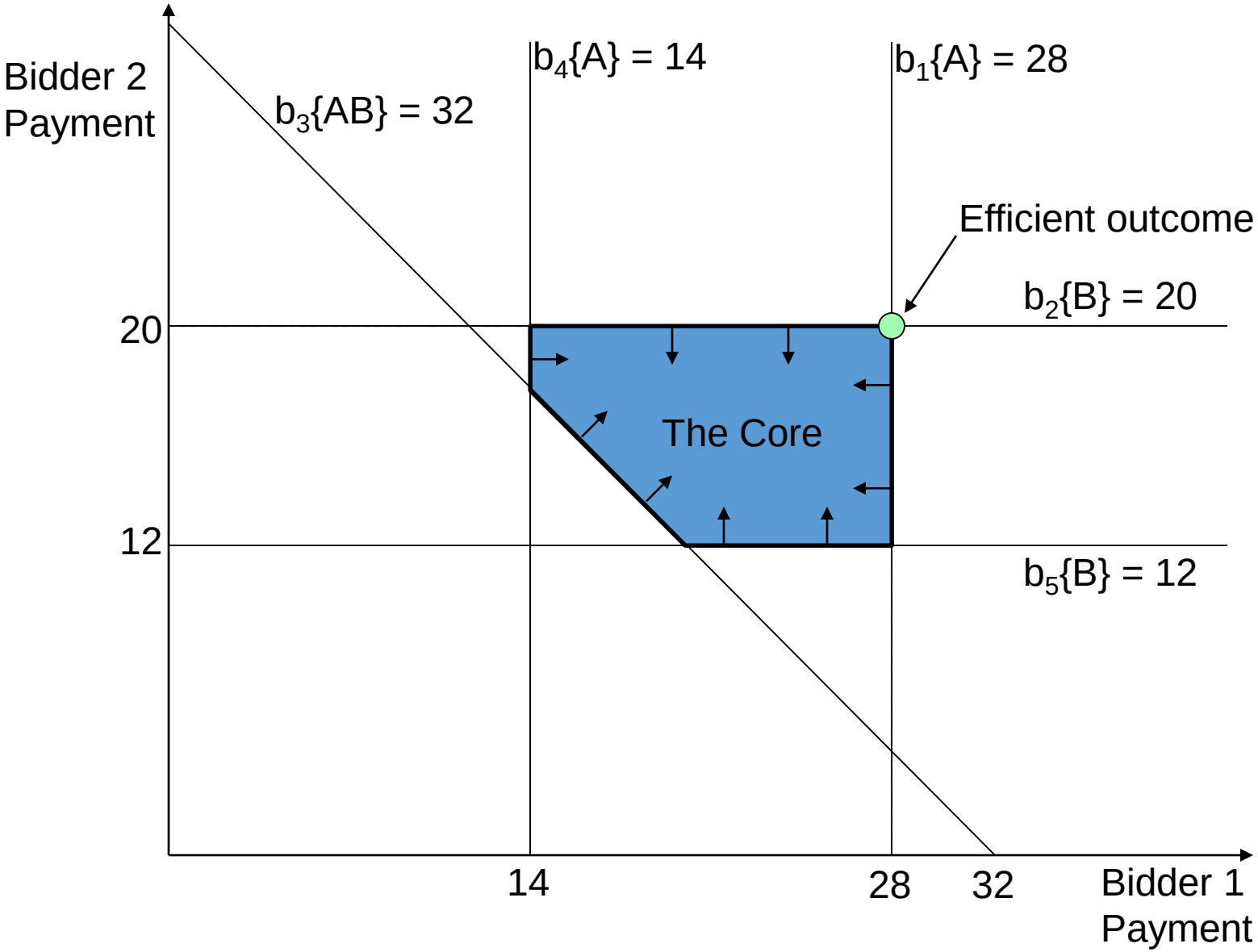
Winners

- $b_3\{AB\} = 32$

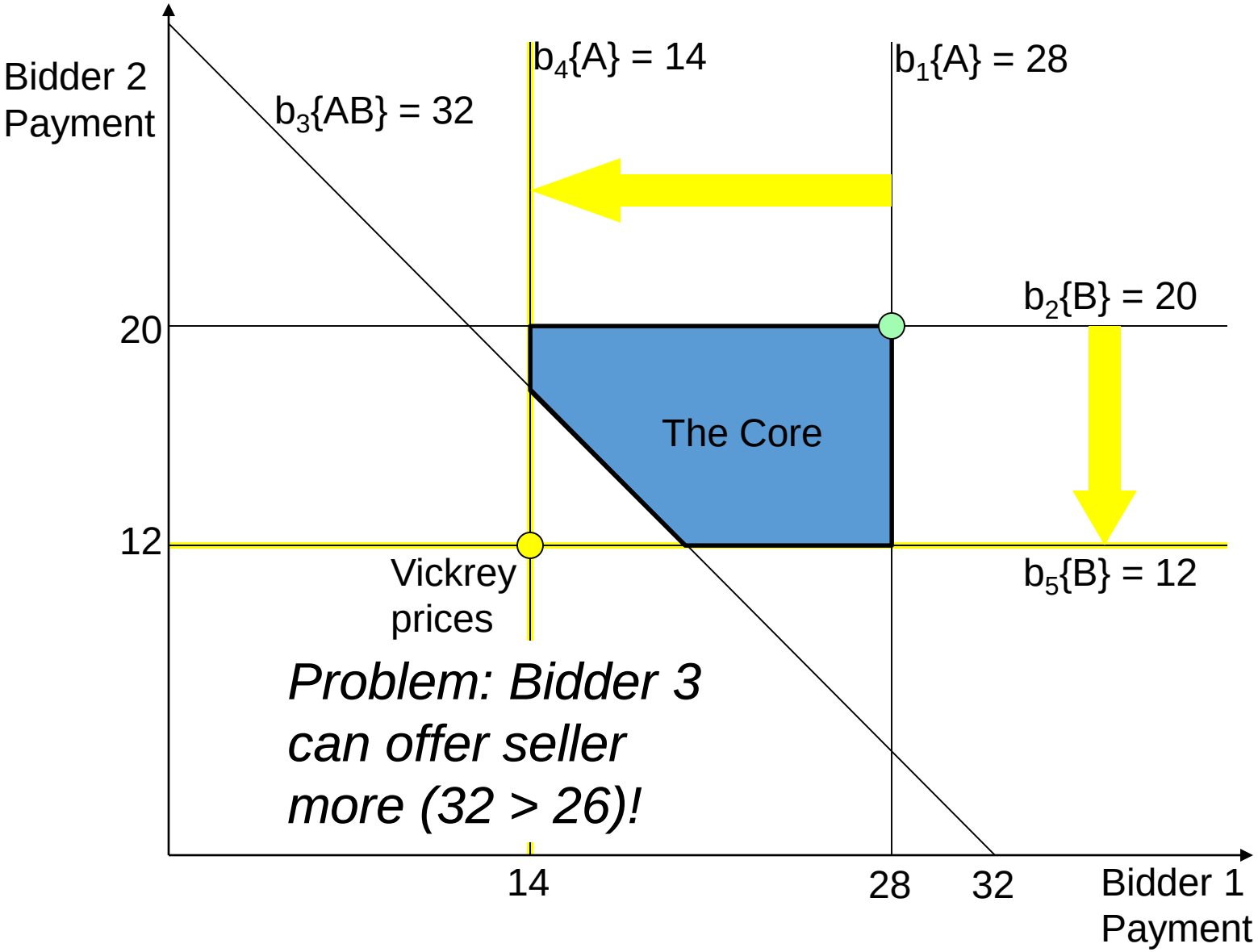
Vickrey prices:

- $b_4\{A\} = 14$ $p_1 = 14$
- $b_5\{B\} = 12$ $p_2 = 12$

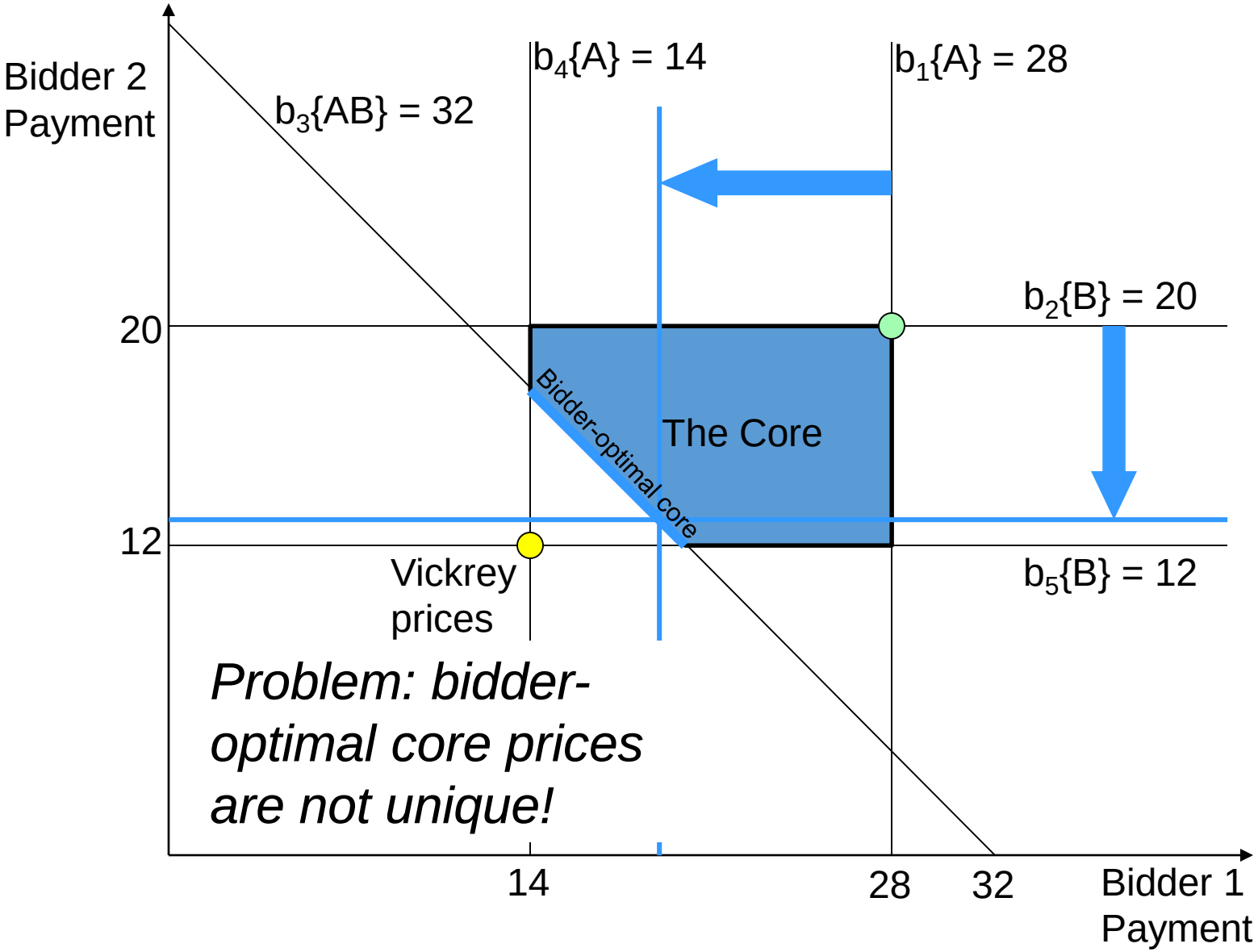
The Core


Bidder 2
Payment
$b_3\{AB\} = 32$
$b_4\{A\} = 14$
$b_1\{A\} = 28$
Efficient outcome
$b_2\{B\} = 20$
20
The Core
12
$b_5\{B\} = 12$
14
28
32
Bidder 1
Payment

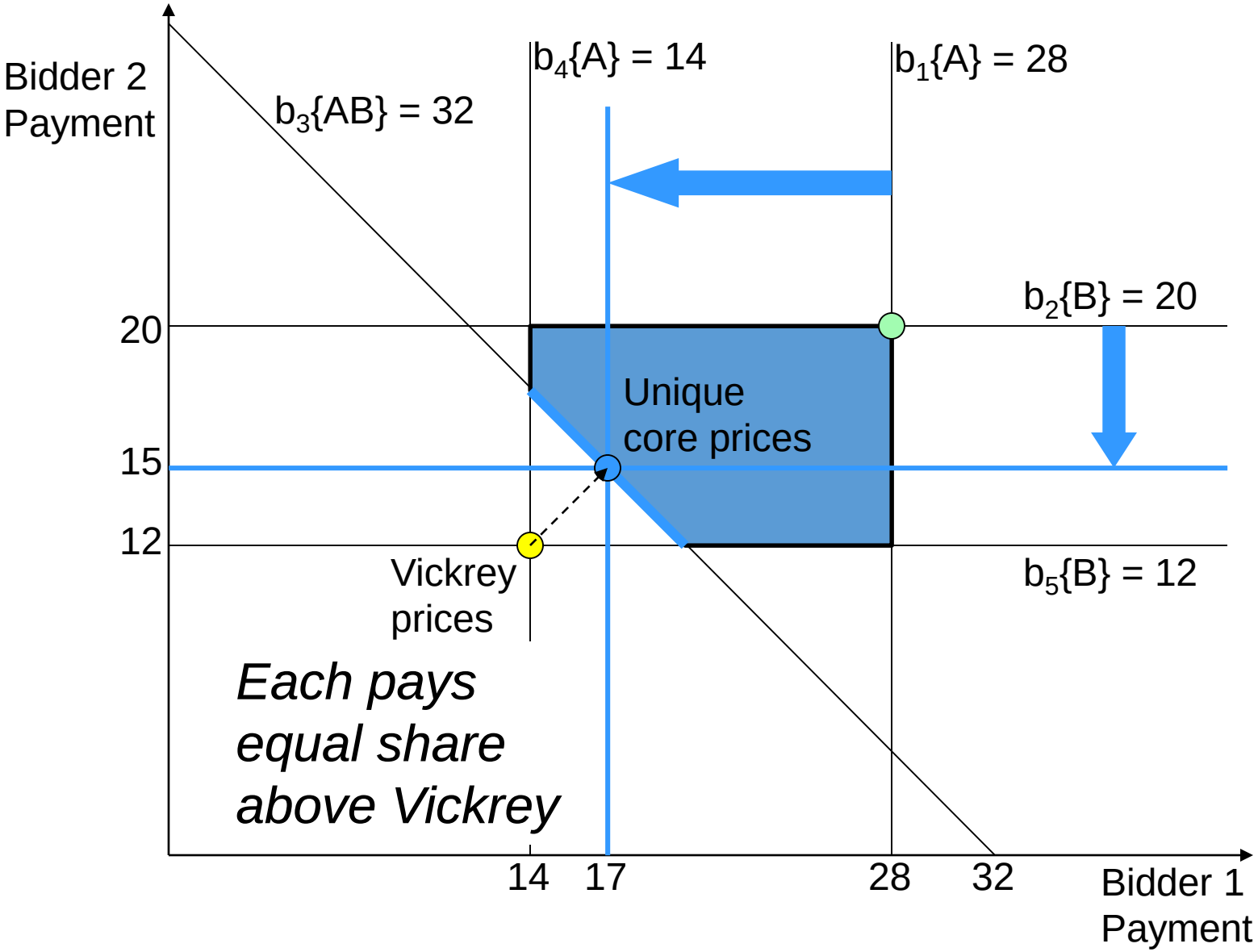
Vickrey prices: How much can each winner's bid be reduced holding others fixed?



Bidder-optimal core prices: *Jointly* reduce winning bids as much as possible



Core point closest to Vickrey prices



Activity rule

Clock stage performs well

Proposition: With revealed preference w.r.t. final round
If clock stage ends with no excess supply,
final assignment = clock assignment

Supplementary bids can't change assignment;
but can change prices

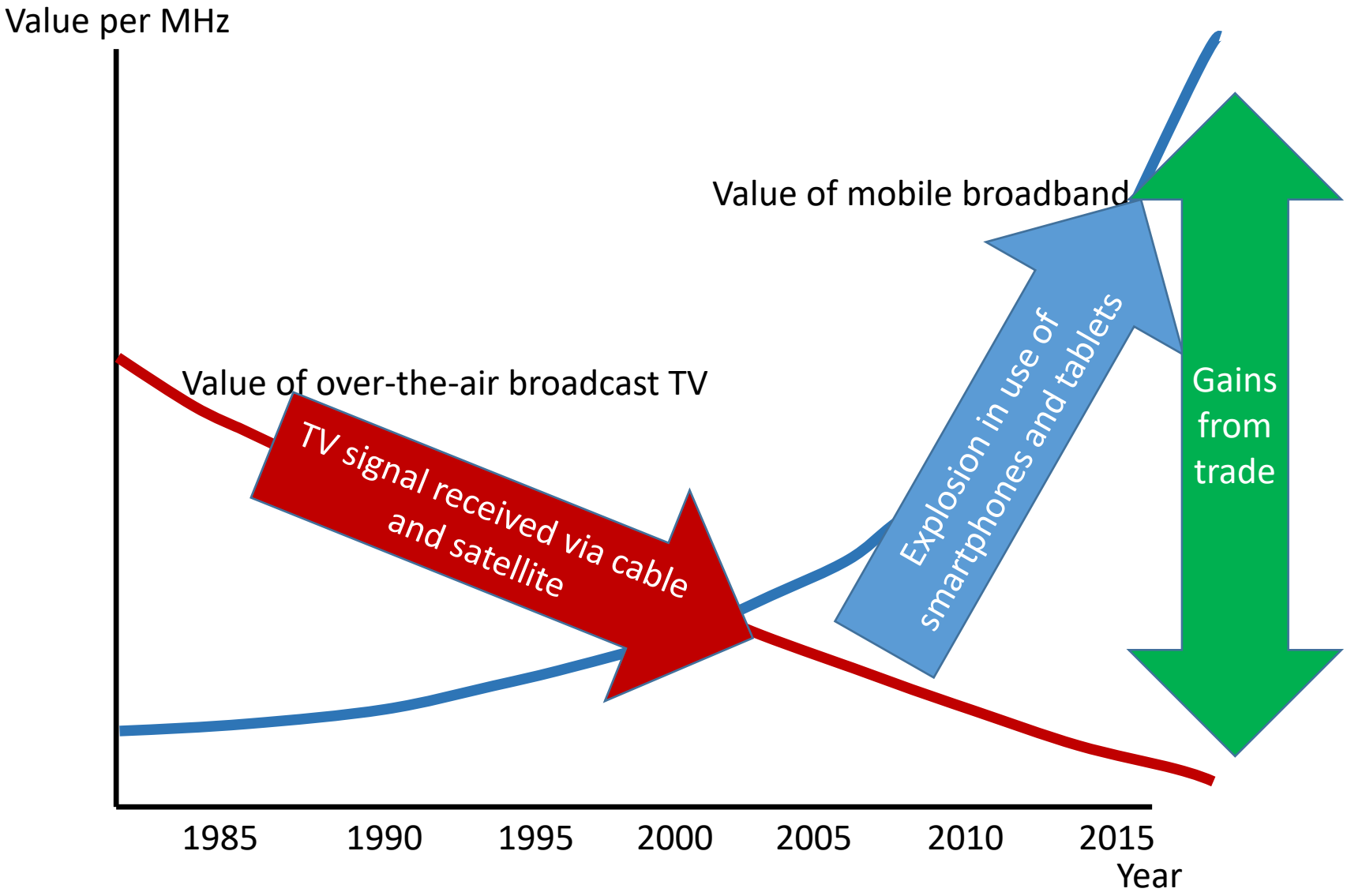
- May destroy incentive for truthful bidding in supplementary round
- Supplementary round still needed to determine competitive prices
- Possible solutions
  - *Do not reveal demand at end of clock stage; possibility of excess supply motivates more truthful bidding (Canada 700 MHz)*
  - *Do not impose final price cap (UK 4G)*

Summary:
CCA is an important tool

- Eliminates exposure
- Reduces gaming
- Enhances substitution
- Allows auction to determine band plan, technology
- Readily customized to a variety of settings
- Many other applications

Broadcast Incentive Auction
29 March 2016

Motivation


Value per MHz
Value of mobile broadband
Value of over-the-air broadcast TV
TV signal received via cable and satellite
Explosion in use of smartphones and tablets
Gains from trade
1985
1990
1995
2000
2005
2010
2015
Year

What is the Incentive Auction?

- The world's most complicated auction!

Goal: clear broadcast spectrum, and repurpose for wireless use

- Consumer demand for broadcast TV has waned, while demand for mobile broadband keeps increasing
- Spectrum in use for broadcast television is very desirable
  - Excellent propagation characteristics
- Convert a set of 6MHz channels into 5+5MHz paired wireless blocks
  - Ex: 21 channels = 126MHz of spectrum = 10 paired blocks + guard bands

What is the Incentive Auction?

- Auction has been in the works for a long time
  - Part of the FCC's National Broadband Plan released in 2010
  - Initiated by Spectrum Act legislation passed in 2012
  - Initial design released in 2014; final design released June 2015
  - Began 29 March 2016; ends late 2016 or early 2017
  - Stage 1, reverse auction ended 29 June 2016; revenue requirement $88 billion

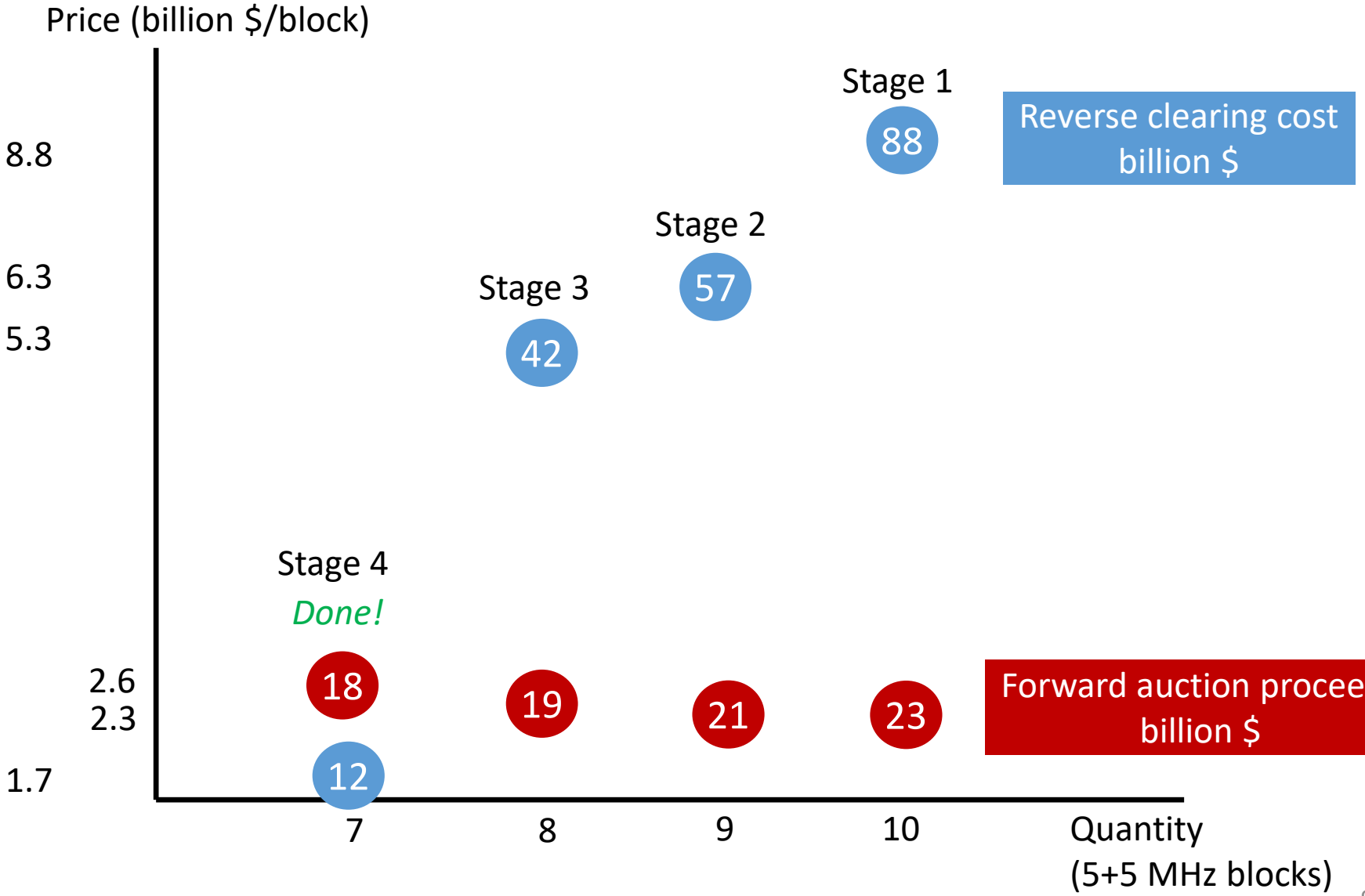
- Auction involves many novel challenges
  - Combines both a reverse and a forward auction into a single process
  - Clearing television spectrum is a hard problem
  - Interplay between forward and reverse auctions introduces additional complexity

Auction summary
29 March 2016 to 10 February 2017

- 16 Oct: FCC announces opening price for each station
- 29 Mar: Station decides whether to accept opening price (participate)
- 29 Apr: FCC optimization (min impairment) to determine clearing target
  - Largest target with impairment < equivalent of 1 nationwide block (10% at 126MHz)
- Stage 1: initial clearing target (126MHz, 10 blocks)
  - 31 May-29 Jun: Reverse auction to determine clearing cost ($88 billion)
  - 16-30 Aug: Forward auction to determine auction proceeds ($22 billion)
- Stage 2: reduce clearing target (114MHz, 9 blocks)
  - 10 Sep-13 Oct: Reverse *continues* with lower target ($57 billion)
  - 19 Oct-19 Oct: Forward *continues* with fewer blocks ($21 billion)
- Stage 3: reduce clearing target (108MHz, 8 blocks)
  - -: Reverse *continues* with lower target ($42 billion)
  - -5 Dec: Forward *continues* with fewer blocks ($19 billion)
- Stage 4: reduce clearing target (84MHz, 7 blocks)
  - 13 Dec-13 Jan: Reverse *continues* with lower target ($12 billion)
  - 18 Jan-10 Feb: Forward *continues* with fewer blocks ($18 billion)
- End: FCC optimization to determine channel assignments

Auction progress

29 March 2016 to 10 February 2017



Keys features of good design

- Simple expression of supply and demand
  - Station: at this lower price are you still willing to clear?
  - Carrier: at this higher price how many blocks do you want?
- Monotonicity
  - Reverse: prices only go down (excess supply)
  - Forward: prices only go up (excess demand)
- Activity rule
  - Reverse: station exit is irreversible
  - Forward: 95% activity requirement

Reverse auction (broadcasters: supply side)

- Identifies prices and stations to be cleared to achieve target

- There are many different ways for broadcasters to participate
  - Relinquish their broadcast license entirely
  - Move to a lower band (change from UHF to VHF)
  - Share a channel and facilities with another broadcaster

- Decision to participate is voluntary
  - Any broadcaster that does not participate can continue broadcasting with their current coverage, but channel may change

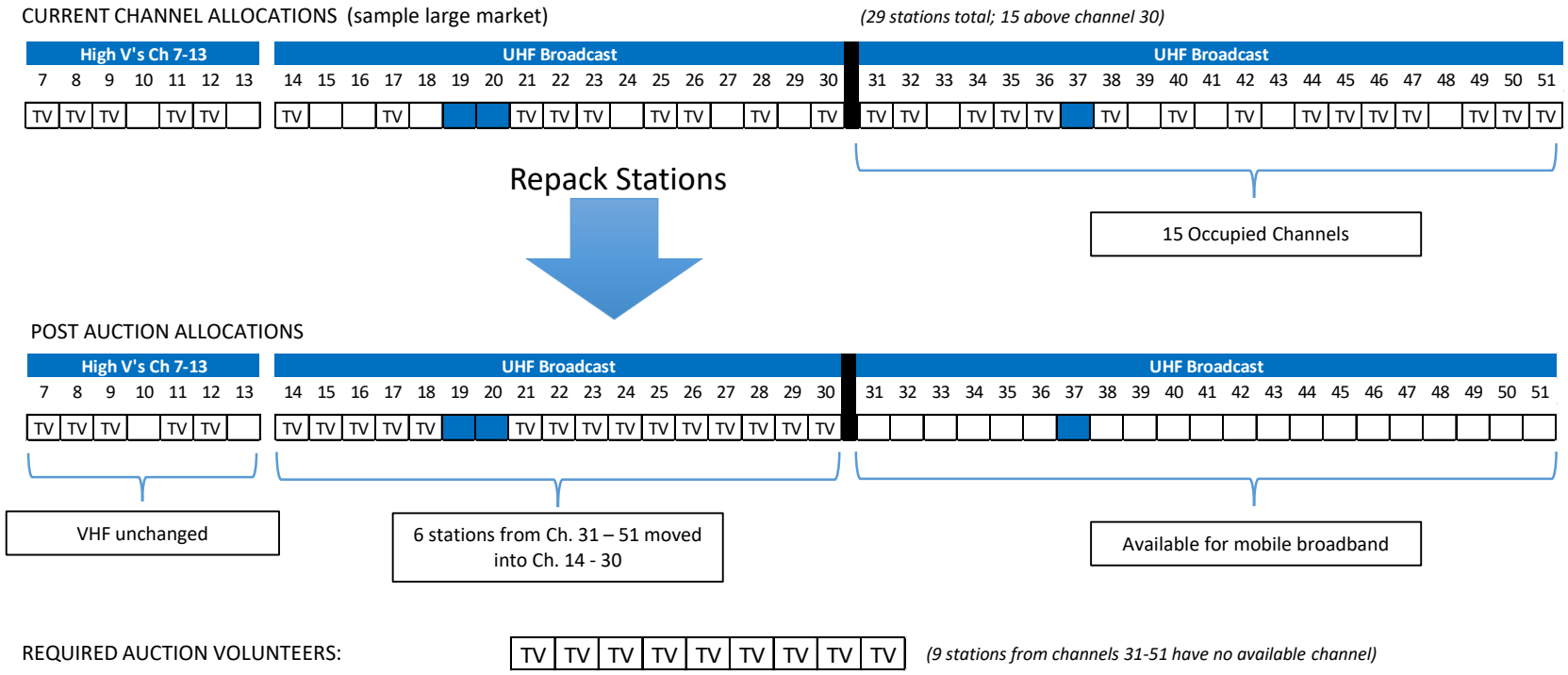
Forward auction (carriers: demand side)

- Ascending clock, rather than simultaneous multiple round

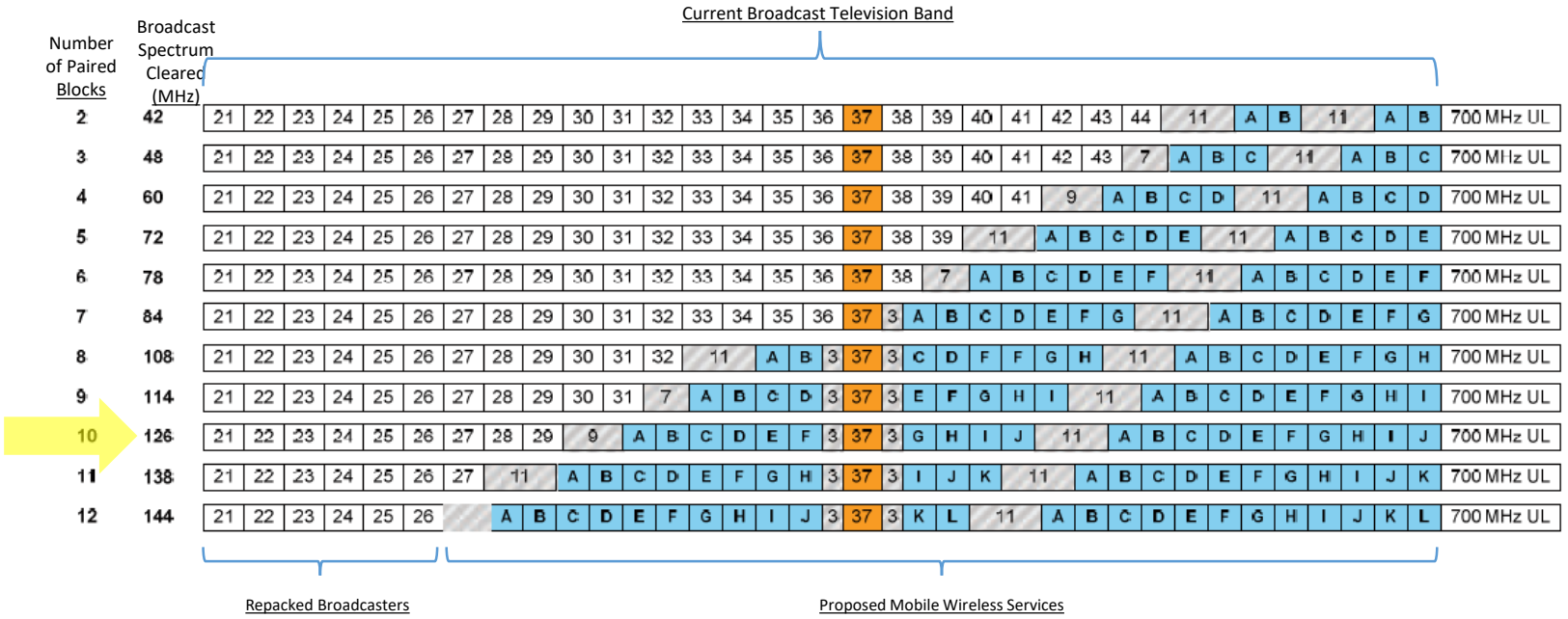
- Issue: participation in reverse auction determines licenses on offer
  - Nonparticipating broadcasters *must* be assigned a channel
  - FCC needs to impair some licenses if too many nonparticipants

- Issue: closing requires forward auction to generate enough revenue
  - Must pay for reverse auction payments + relocation costs + FCC costs
  - If closing conditions are not met, FCC holds an extended round to increase bidding in top-40 markets, or continues process with a lower clearing target

What is “Repurposing broadcast spectrum”?



Possible band plans



Notes:

1. Numbers in the table represent current broadcast television channels
2. Letters in the table represent paired blocks for mobile wireless services
3. Grey blocks represent guard bands and their width (in MHz)
4. Impaired markets will have a band plan from the table, but not at the nationwide clearing target
5. Band plan above stops at UHF channel 21 (does not show UHF channels 14 to 20)

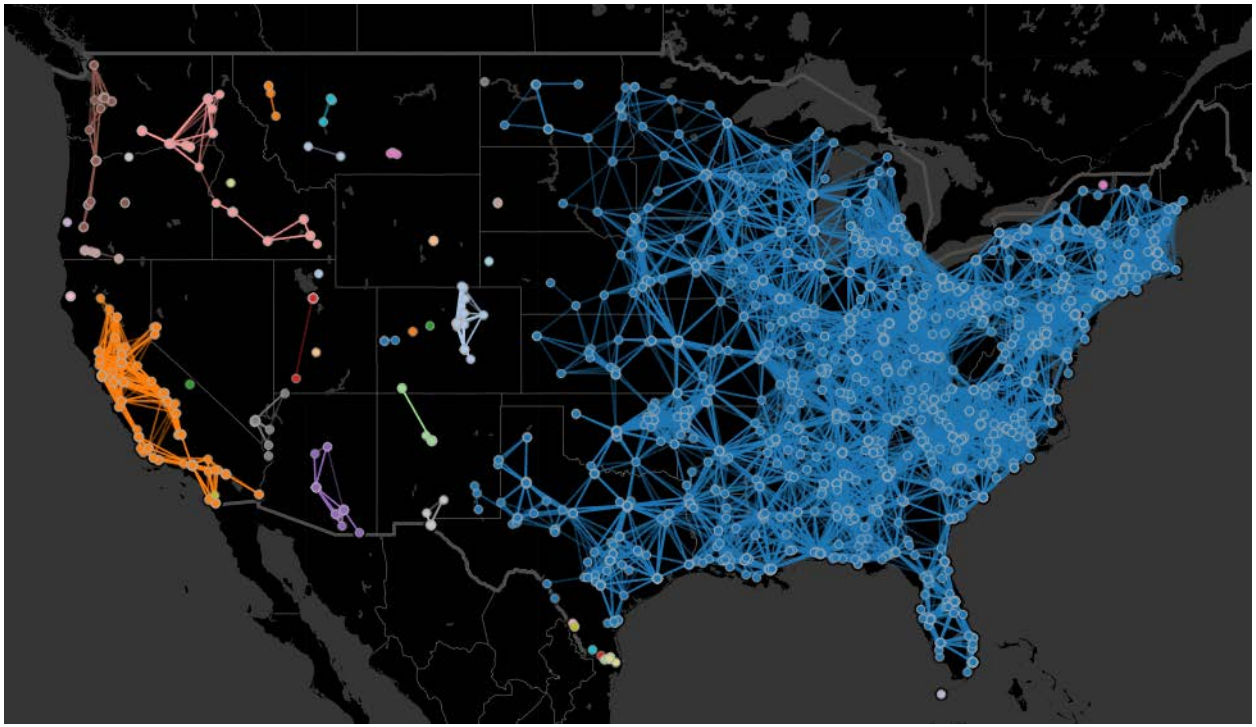
Why is this complicated?

- Have a supply side (broadcasters) and demand side (wireless carriers), so why not just determine where supply meets demand?

- Issue: the supply side is extremely complicated
  - “Buy stations until # stations = # channels” only works at local scale
  - Two stations can only use the same channel if they do not cause interference

- Interference between stations creates a complex set of constraints
  - Depends on physical factors: distance, transmitting power, terrain, antenna…
  - If stations interfere strongly enough, cannot even be on *adjacent* channels
  - Large markets can interfere with each other, e.g. New York and Philadelphia

Nationwide interference constraints



Finding channel assignments

- Finding a *nationwide* channel assignment is extremely complicated
  - Hundreds of thousands of interference constraints between stations
  - Border regions must respect treaties with Canada and Mexico
  - Some channels reserved for emergency communications in many markets

- Checking if a set of stations can be repacked is computationally hard
  - Equivalent to classic Satisfiability (SAT) problem from computer science
  - No generally efficient solution known; widely believed not to exist
  - The auction needs to make hundreds of thousands of these checks
  - Fortunately, this can be made (mostly) efficient in practice

Design of the reverse auction

The reverse auction is a scored descending clock auction:

- Each television station is assigned a score (starting price)
- A single clock ticks down from 100% to 0%; at each time step:
  - Every station is offered a price of (score)×(current %)
  - If a station rejects this offer, it is assigned a channel
  - Then if any station no longer can be assigned a channel, that station is bought

Note: this ignores many factors that make the auction more complex

Note: immediately buying stations with no available channels ensures that active stations always have a feasible channel assignment

What is the “right” scoring rule?

- Choice of scoring rule has a huge impact on auction outcomes
  - Determines opening prices, and hence participation levels
  - Determines exit order and payments
- Exit order will have a lasting impact on broadcast television
  - Nearby markets often have to “share” channels due to interference
  - If stations in Philadelphia all exit before stations in New York, then post-auction Philadelphia will have more broadcast television than New York
  - This phenomenon is repeated across the country, both between pairs of large markets, and between large markets and nearby small markets.

What is the “right” scoring rule?

FCC scoring rule:

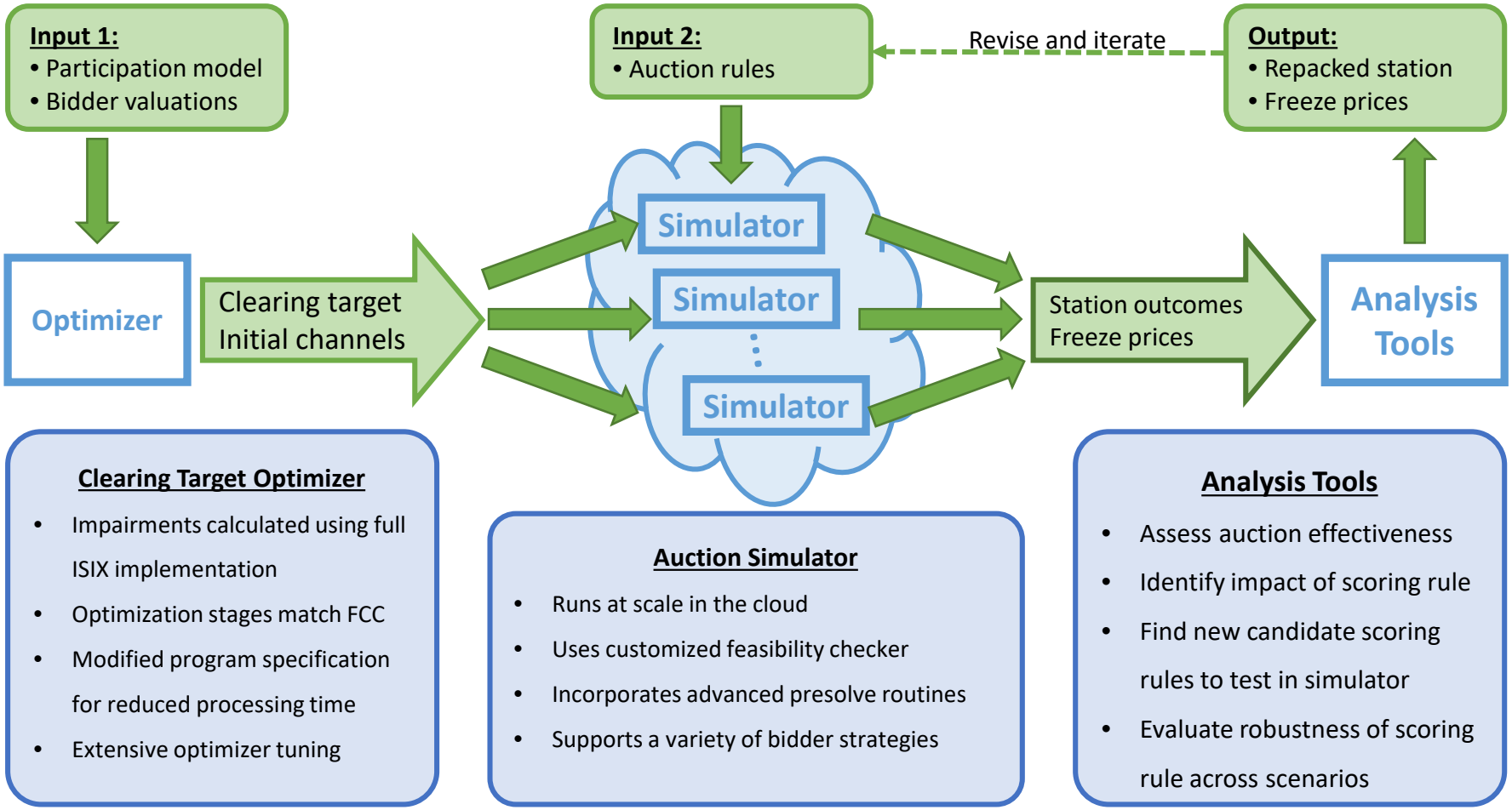
Geometric mean of population served and # of interference constraints

- Population served gives a proxy for geographic area
  - Interference propagates further than service; stations in markets near major markets often serve small populations but interfere with large ones

- # of interference constraints gives a proxy for packing compatibility
  - Not all interference constraints are equal: some never bind in the auction
  - Many other potential measures suggested by graph theory
  - May be better to use simulation to determine repackability

Methodology

- Simulate reverse auction
  - To test implications of alternative auction rules
  - To evaluate alternative bidding strategies
- Key assumptions
  - Station participation decisions
  - Station reservation values
  - Straightforward bidding (initially)


Input 1:
• Participation model
• Bidder valuations
Input 2:
• Auction rules
Revise and iterate
Output:
• Repacked station
• Freeze prices
Optimizer
Clearing target
Initial channels
Simulator
Simulator
Simulator
Station outcomes
Freeze prices
Analysis Tools
Clearing Target Optimizer
• Impairments calculated using full ISIX implementation
• Optimization stages match FCC
• Modified program specification for reduced processing time
• Extensive optimizer tuning
Auction Simulator
• Runs at scale in the cloud
• Uses customized feasibility checker
• Incorporates advanced presolve routines
• Supports a variety of bidder strategies
Analysis Tools
• Assess auction effectiveness
• Identify impact of scoring rule
• Find new candidate scoring rules to test in simulator
• Evaluate robustness of scoring rule across scenarios

Example: scoring rule

- Trade-off between reverse auction efficiency and clearing cost
  - Efficiency: Emphasize a station's value in clearing (how much it gets in the way)
  - Clearing cost: Price discriminate by offering stations with low broadcast value less
  - Broadcast population (broadcast value) vs. precluded population (clearing value)
- But to clear maximum spectrum, FCC must be concerned about clearing cost

Conclusions

- The incentive auction is hugely complicated and hugely important
  - First of its kind, with many novel complications
  - Won't be the last of its kind: every country faces this spectrum issue
- Critical to analyze and evaluate the design decisions
- Simulation is a useful way to assess design and robustness to strategic behavior

Important lessons

- No auction design is perfect
- Design must be customized for setting
  - Simultaneous ascending clock
    - Simple settings (upcoming UK)
  - Combinatorial clock
    - Packaging is essential (UK 4G, Canada 700 MHz)
  - Two-sided clock
    - Incentive auction in US
- Never ignore essentials
  - Encourage participation
  - Demand performance
  - Avoid collusion and corruption

The Future of Mobile Communications

An Open Access Wireless Market

Supporting Public Safety, Universal Service, and Competition

Peter Cramton

Linda Doyle

From monopoly to vibrant competition

Monopoly

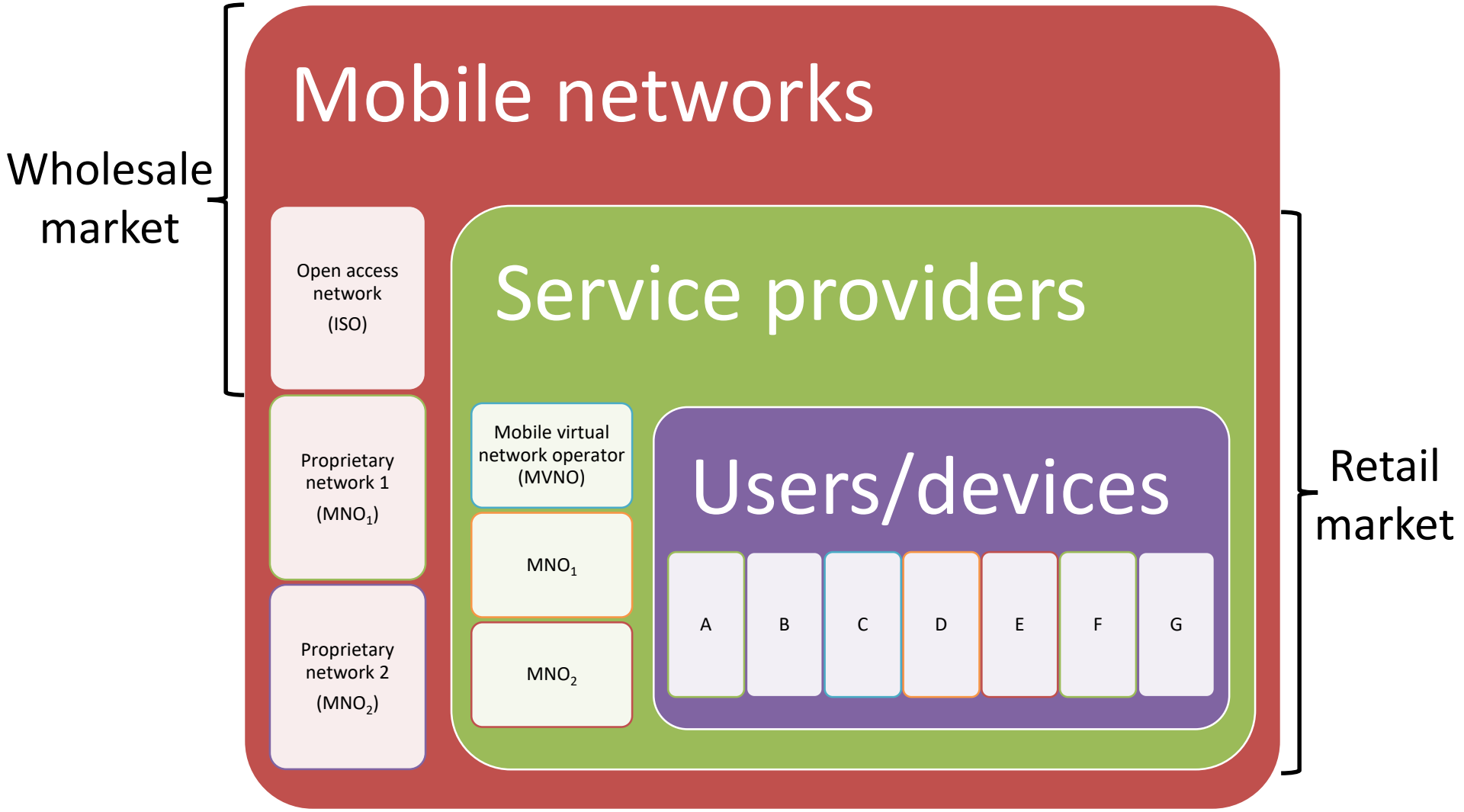
- Original "Ma Bell" telecommunications

Oligopoly

- Spectrum auctions
- Mobile communications

Competition

- Open access wireless market
- Internet ecosystem of innovation

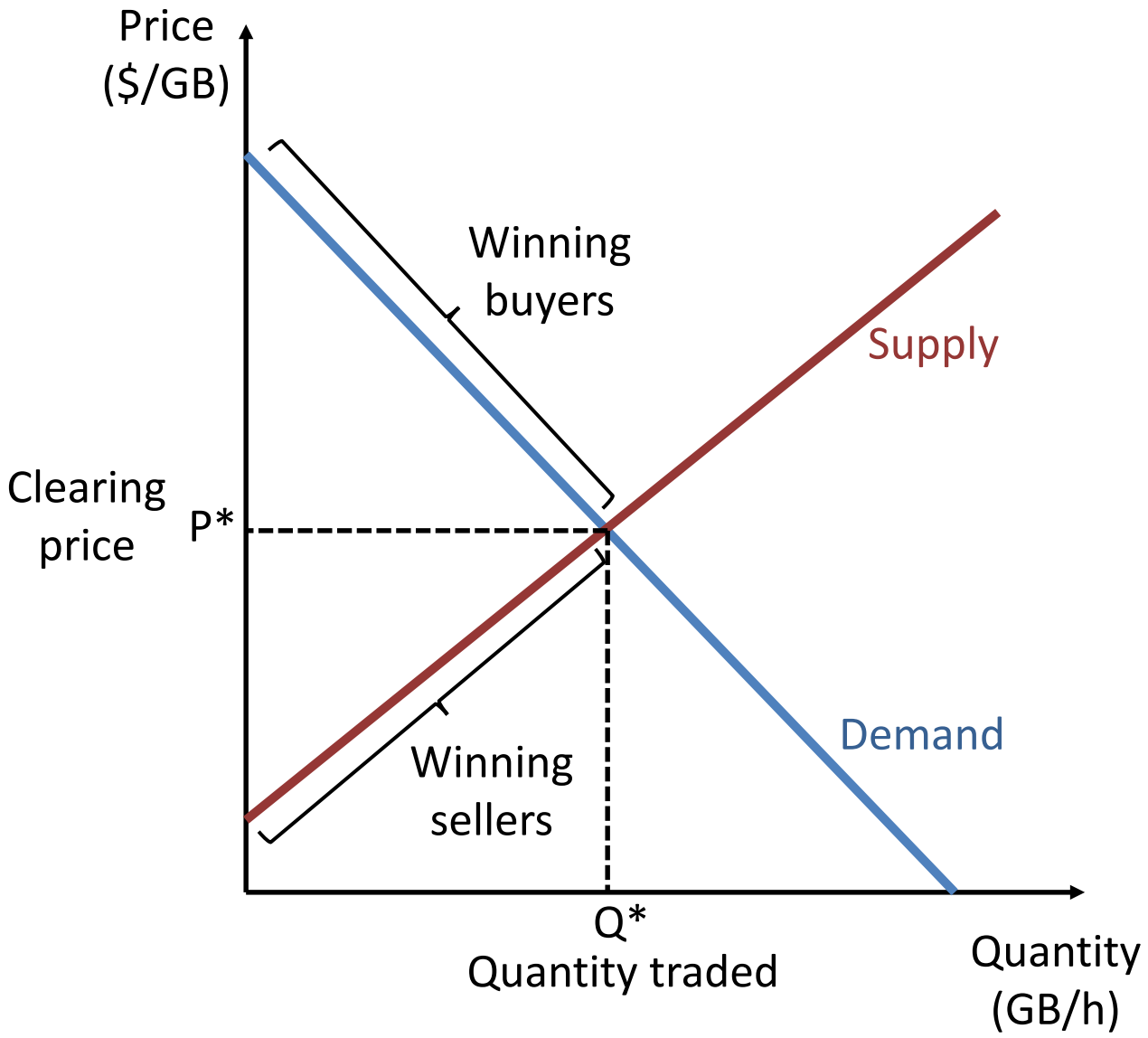


Same market model as electricity successfully operating for two decades

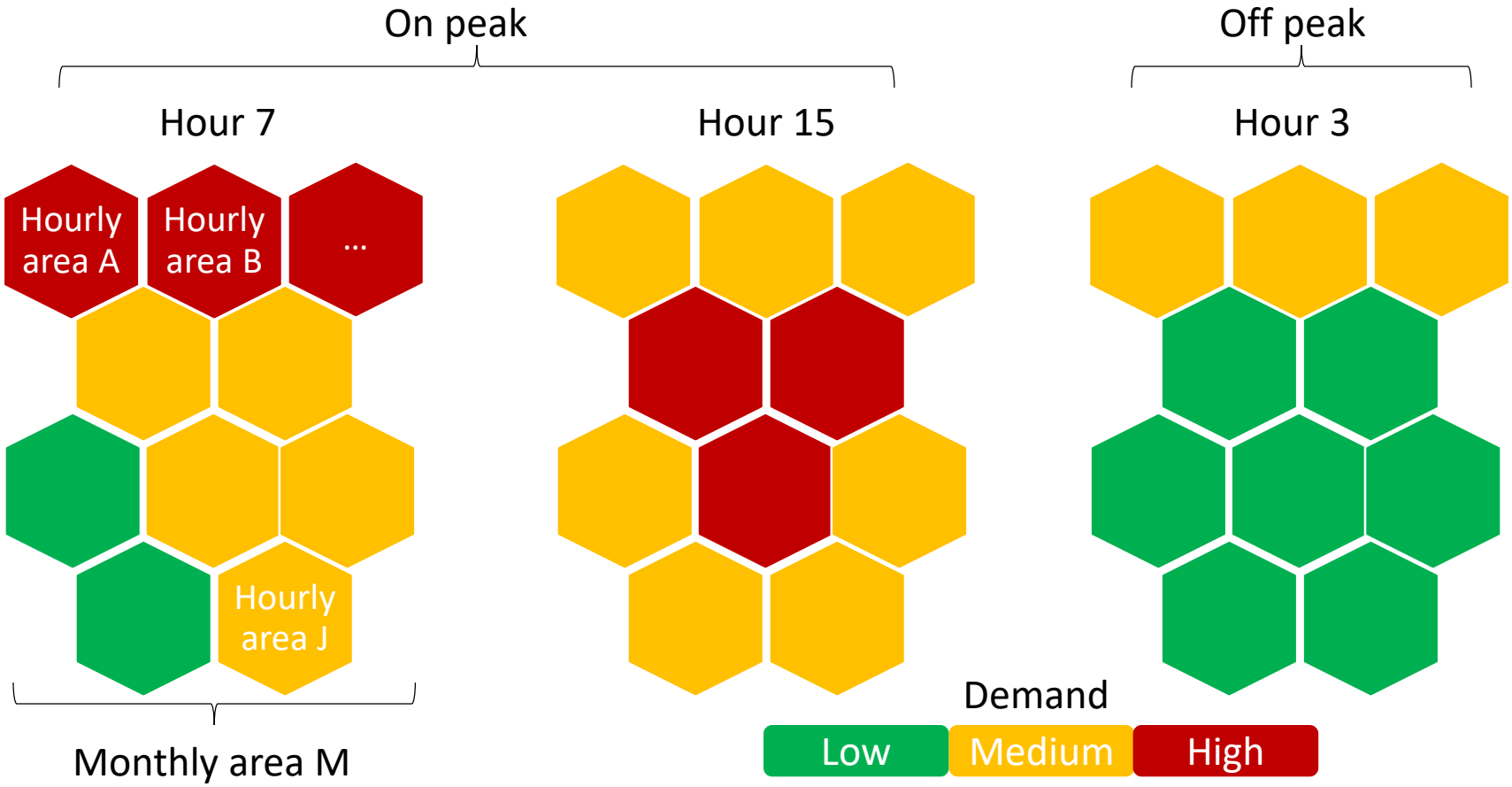
Product design

- Product should be directly valued by consumer
  - Network throughput at particular location and time interval
  - A market for throughput not spectrum
  - Energy (MWh) in an electricity market
- Aggregation in both time and location to simplify and improve liquidity
  - Example: Particular cell over one hour (GB/h)

All markets use single-price auction



Multiple opportunities to trade: Yearly, monthly, hourly



Yearly aggregates monthly aggregates hourly in time and location

Service provider estimates demand and stages purchase in three markets

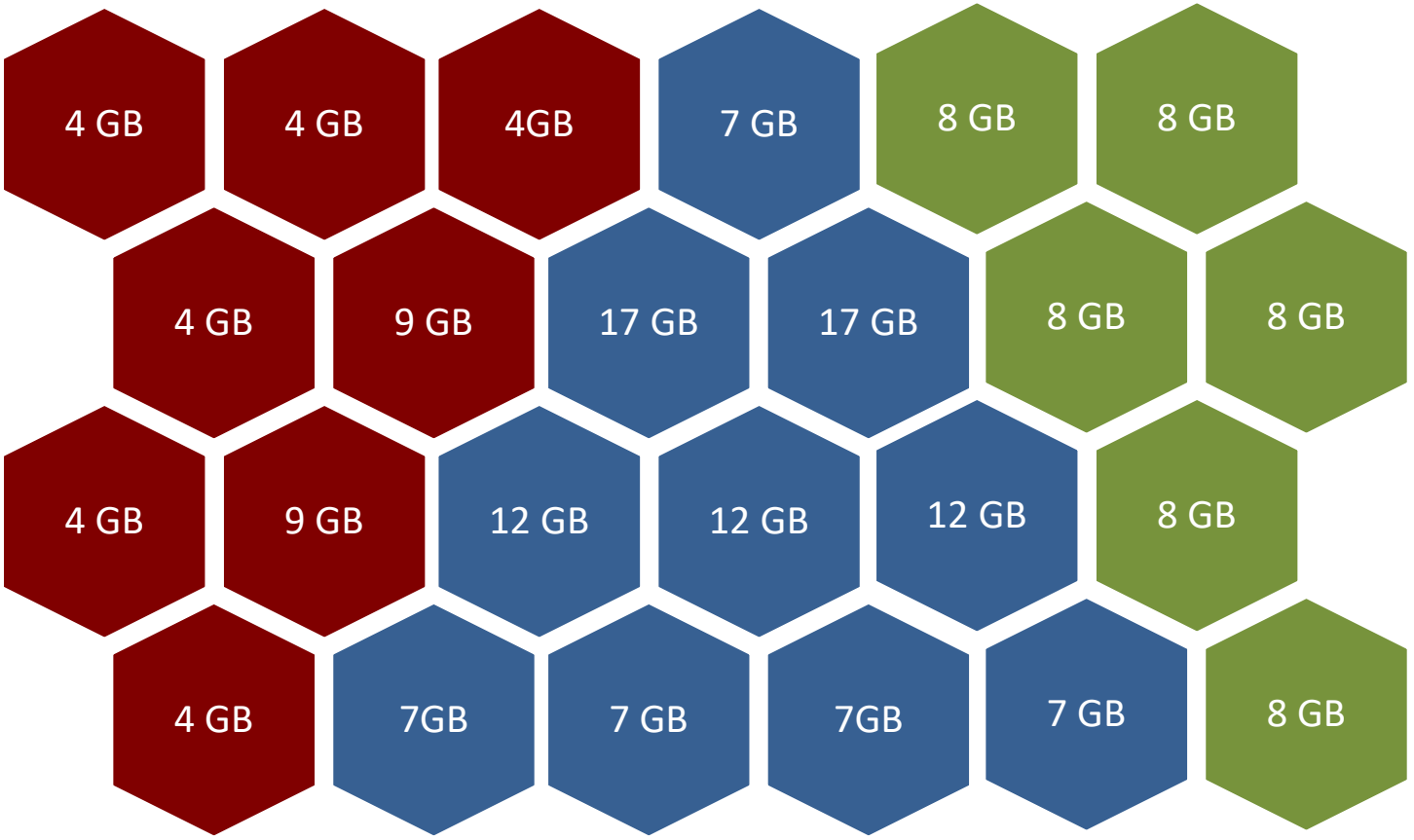
Yearly auction = buy 165 GB per hour, for every peak hour in the year, in the yearly area

Refine estimate and make adjustment in monthly market

Yearly auction = buy 165 GB per hour, for every peak hour in the year, in the yearly area

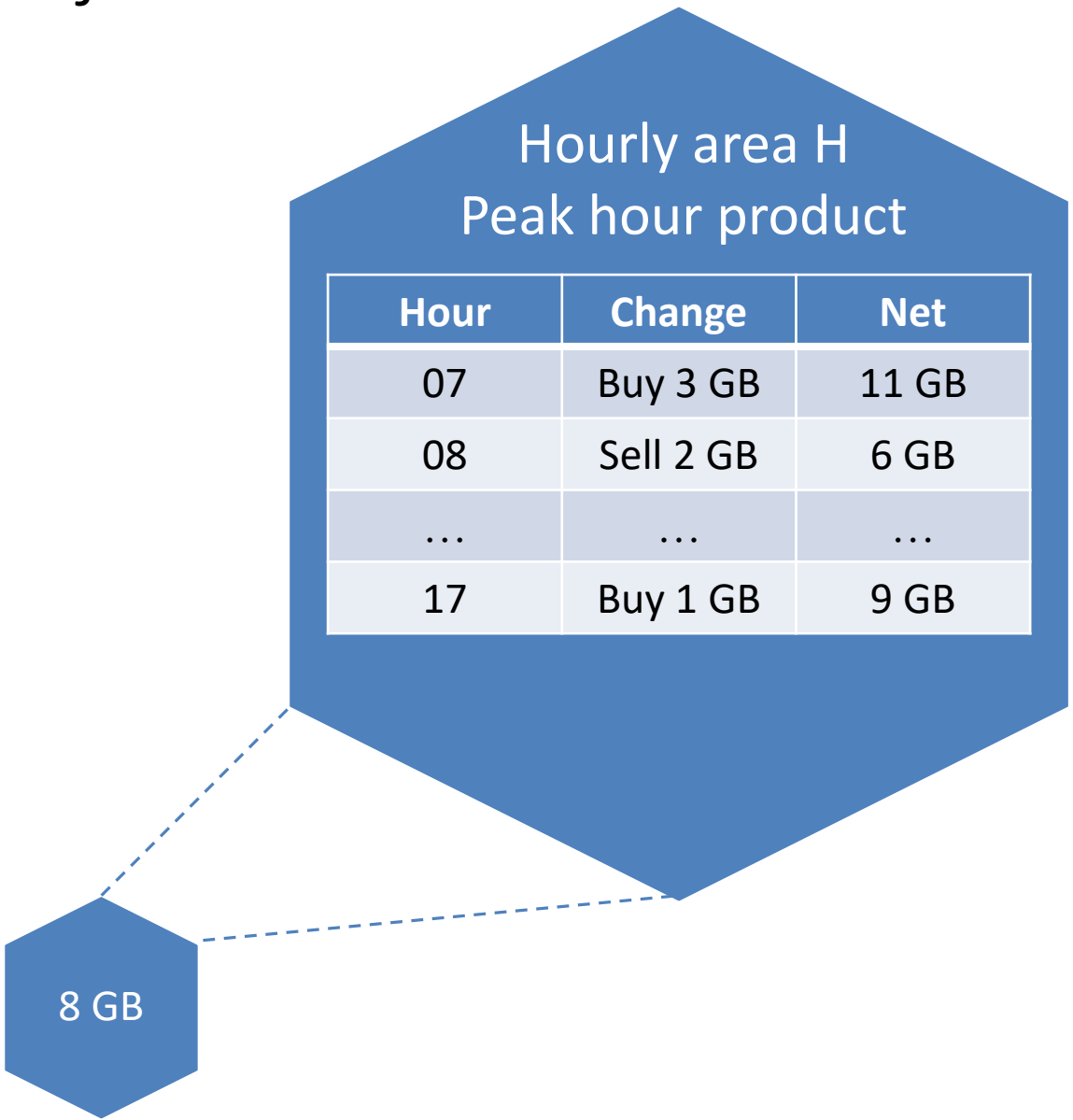
Monthly auction = sell 8 GB per hour, for every peak hour in the month, in the red area

Monthly auction = buy 15 GB per hour, for every peak hour in the month, in the green area



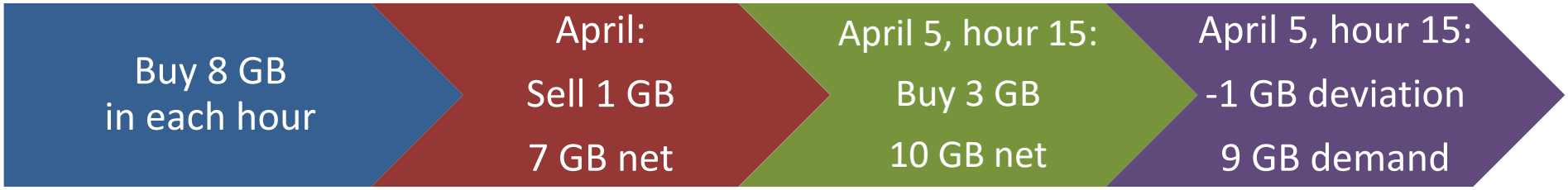
Monthly auction = buy 20 GB per hour, for every peak hour in the month, for the blue area

Finalize estimate one hour ahead and make final adjustment to demand



Sequence of auctions

Example



- Three opportunities to trade
  - Reduces risk of service provider
  - Facilitates planning of service provider
  - Provides price transparency
  - Mitigates market power

Prototype auction platform

- To illustrate market
- Demonstrate proof of concept

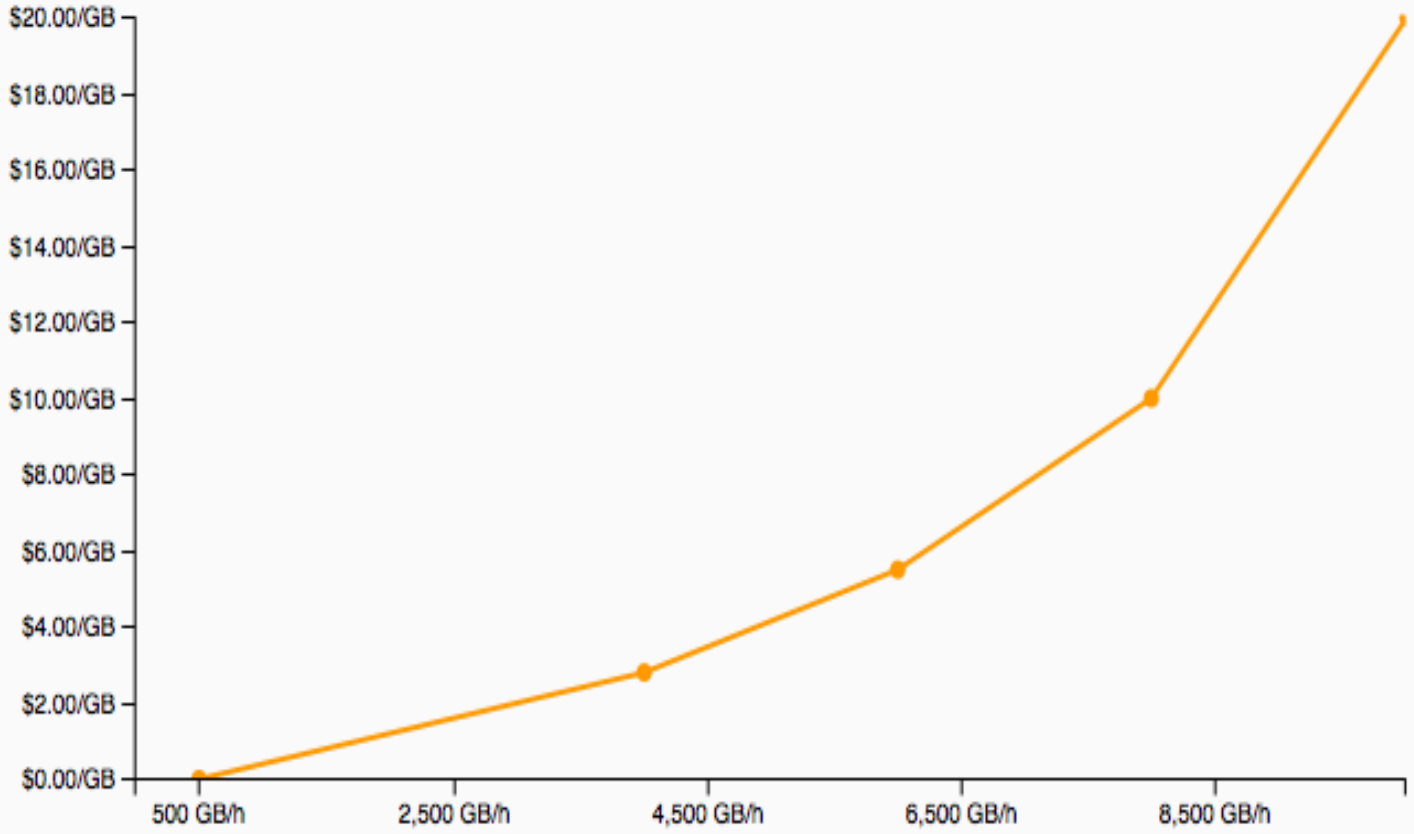
Auction design

- Uniform-price auction for each product
- Preferences expressed as piecewise-linear strictly-decreasing demand curves
  - Consistent with underlying preferences
  - Unique clearing prices and quantities
- Yearly and monthly auctions: simultaneous ascending clock
- Hourly auction: sealed bid

Current Published Supply Curve for Manhattan (Peak)

Select a product to view its supply curve calculated from the relative supply curve currently in the system.

Manhattan (Peak)



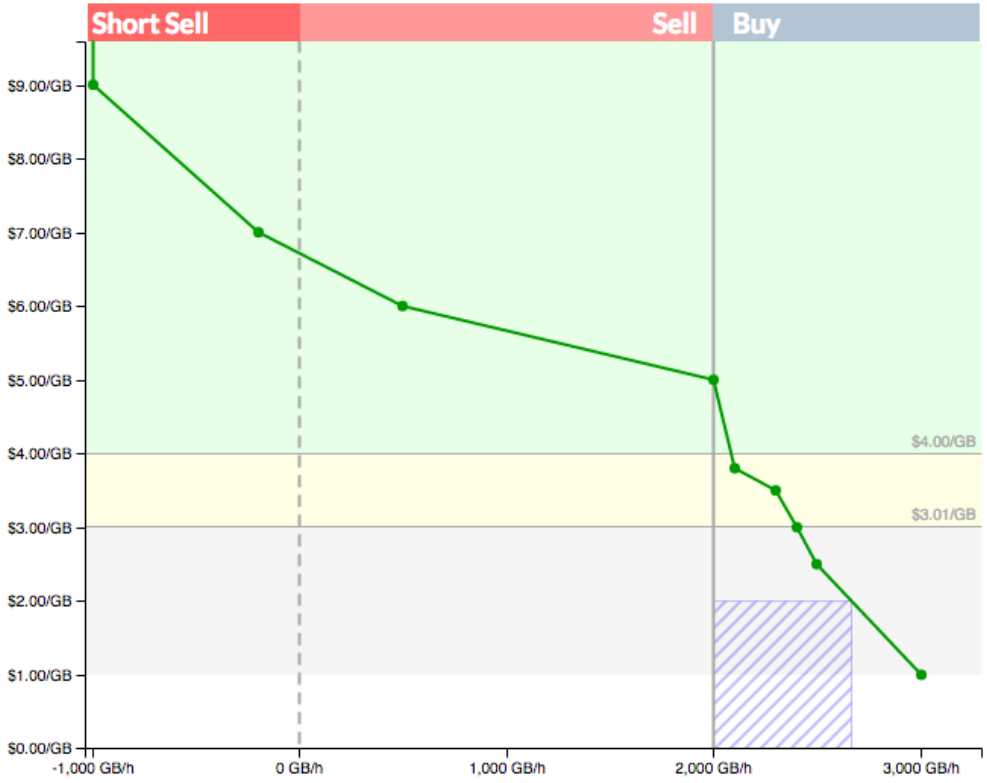
Sample demand for bidder

Manhattan (peak) monthly

Manhattan (Peak) At $ | /GB hold GB/h Add Cancel

Your Forward Position: 2,000.000 GB/h **Published Maximum Supply:** 10,000.000 GB/h

	Price	Quantity	Change in Quantity	Commitment (180 hours)
Future Rounds				
✉	$9.00/GB	-1,000.000 GB/h	-3,000.000 GB/h	-$4,860,000
✉	$7.00/GB	-200.000 GB/h	-2,200.000 GB/h	-$2,772,000
✉	$6.00/GB	500.000 GB/h	-1,500.000 GB/h	-$1,620,000
✉	$5.00/GB	2,000.000 GB/h	0.000 GB/h	$0
Current Round				
	$4.00/GB	***2,083.333 GB/h***	***83.333 GB/h***	***$60,000***
✉*	$3.80/GB	2,100.000 GB/h	100.000 GB/h	$68,400
✉*	$3.50/GB	2,300.000 GB/h	300.000 GB/h	$189,000
Past Rounds				
	$3.00/GB	***2,400.000 GB/h***	***400.000 GB/h***	***$216,000***
🔒	$2.50/GB	2,500.000 GB/h	500.000 GB/h	$225,000
↑	***$2.00/GB***	***2,666.667 GB/h***	***666.667 GB/h***	***$240,000***
Price Floor				
🔒	$1.00/GB	3,000.000 GB/h	1,000.000 GB/h	$180,000



Addressing hourly deviations between actual and purchased demand

- Neither system operator nor service provider can *control* demand perfectly to assure quantity consumed = quantity won
- Deviations are inevitable
- Final settlement should motivate service providers to limit deviations

Hourly settlement for deviations

- p_{hk} = price in hour *h* in area *k* that balances as-bid demand with estimated supply
- q_{ihk} = total quantity bought by bidder *i* in hour *h* in hourly area *k* (includes yearly, monthly, and hourly net purchases)
- Q_{ihk} = actual quantity consumed by bidder *i* in hour *h* in hourly area *k*
- $D_{ihk} = Q_{ihk} - q_{ihk}$ = deviation between actual quantity consumed and quantity bought
- *Tolerance* = percentage tolerance band (e.g., 10%); no penalty if deviation is within Tolerance
- *Penalty Factor* = a factor that is applied to square deviations above Tolerance
- Adjustment for deviations in the real-time market is $Adjustment_{ihk} = p_{hk} \times D_{ihk} + Penalty_{ihk}$ where
- $$Penalty_{ihk} = \begin{cases} 0 & if \ \frac{|D_{ihk}|}{q_{ihk}} \leq Tolerance \\ Penalty\ Factor \times p_{hk} \times D_{ihk}^2 & if \ \frac{|D_{ihk}|}{q_{ihk}} > Tolerance \end{cases}$$

Standard efficient settlement if deviation is within Tolerance; penalty based on squared deviation outside of Tolerance to induce best estimate and control of demand to match winnings

Likely implementations

- Mexico (competition)
  - 90 MHz of 700 MHz set aside for open access
  - RFP to select implementer in 28 Sep 2016
- United States (public safety)
  - 20 MHz of 700 MHz set aside + $7 billion
  - RFP to select implementer in November 2016
- European Union (merger remedy)
  e.g. UK: Three & O2
  - Proposed mergers leading from 4 to 3 carriers
  - Merged entity allocates portion of network to open access