Competing Network Technologies Winners and Losers

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Acknowledgments

- This is joint work with
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  - Kartik Hosanagar (Penn, Wharton)

- and in collaboration with
  - Andrew Odlyzko (U. Minn)
  - Zhi-Li Zhang (U. Minn)

Outline

- Why this work?
  - Problem formulation and motivations
- Model scope and characteristics
- A brief glance at the machinery
- The insight and surprises
  - Key findings and representative examples
- Conclusion and extensions
  - What next?

Background and Motivations

- Deploying new (network) technologies (and architectures) is rife with uncertainty and challenges
  - Presence of an often formidable incumbent (e.g., today's Internet)
  - Dependencies on what others do (externalities)
  - Migration and upgrade issues (infrastructure wide)
- Can we develop models that provide insight into
  - When, why, and how new technologies succeed?
  - What parameters affect the outcome, and how do they interact?
    - Intrinsic technology quality, price, individual user decisions, etc.
  - To what extent do gateways/converters between old an new technologies influence deployment dynamics and eventual equilibria?

P.S.: The models have applicability beyond networks

Problem Formulation

- Two competing and incompatible technologies
  - Different qualities and price
  - Value of technology also depends on number of adopters (externalities)
    - Tech. 1 is the incumbent
    - Tech. 2 enters the market with zero initial penetration
- Users individually (dis)adopt either technology or none ($0 \leq x_1 + x_2 \leq 1$)
  - Decision based on technology ***utility***
- Gateways/converters offer possible inter-operability
  - Allows users of one technology to communicate with users of the other
    - Independently developed by each technology
  - Gateways/converters characteristics/performance
    - Duplex vs. simplex (independent in each direction or coupled)
    - Asymmetric vs. symmetric (performance/functionality wise)
    - Constrained vs. unconstrained (performance/functionality wise)

Utility Function

Technology 1: $U_1(\theta,x_1,x_2) = \theta q_1+(x_1+\alpha_1\beta x_2) - p_1$

Technology 2: $U_2(\theta,x_1,x_2) = \theta q_2+(\beta x_2+\alpha_2 x_1) - p_2$

- A closer look at the parameters
  - Cost (recurrent) of each technology (p_i)
  - Externalities: linear in the number of adopters – Metcalfe's law
    - Normalized to 1 for tech. 1
    - Scaled by β for tech. 2 (possibly different from tech. 1)
    - α_i, $0 \le \alpha_i \le 1$, $i = 1,2$, captures gateways' performance
  - Intrinsic technology quality (q_i)
    - Tech. 2 better than tech. 1 ($q_2 > q_1$) but no constraint on magnitude, i.e., stronger or weaker than externalities (can have $q_2 > q_1 \approx 0$)
  - User sensitivity to technology quality (θ)
    - Private information for each user, but known distribution

Anchoring the Model

1. IPv4 ↔ IPv6
   – Duplex, asymmetric, constrained gateways

2. Low def. video conf. ↔ High def. video conf.
   – Simplex, asymmetric, unconstrained converters

IPv4 (Tech. 1) $\leftrightarrow$ IPv6 (Tech. 2)

IPv4: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

IPv6: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- Setting
  - We are (eventually) running out of IPv4 addresses
    - Providers will need to start assigning IPv6 only addresses to new subscribers ($p_{\mathrm{IPv4}} = p_1 > p_2 = p_{\mathrm{IPv6}}$)
  - IPv4 and IPv6 similar as "technologies" ($q_1 \approx q_2$ and $\beta = 1$)
- Mandatory IPv6<->IPv4 gateways for transition to happen
  - Most content is ***not*** yet available on IPv6
    - Little in way of incentives for content providers to do it
  - Duplex, asymmetric, constrained converters
- Users technology choice
  - Function of price and accessible content

Low-def. video $\leftrightarrow$ High-def. video

Low-def: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

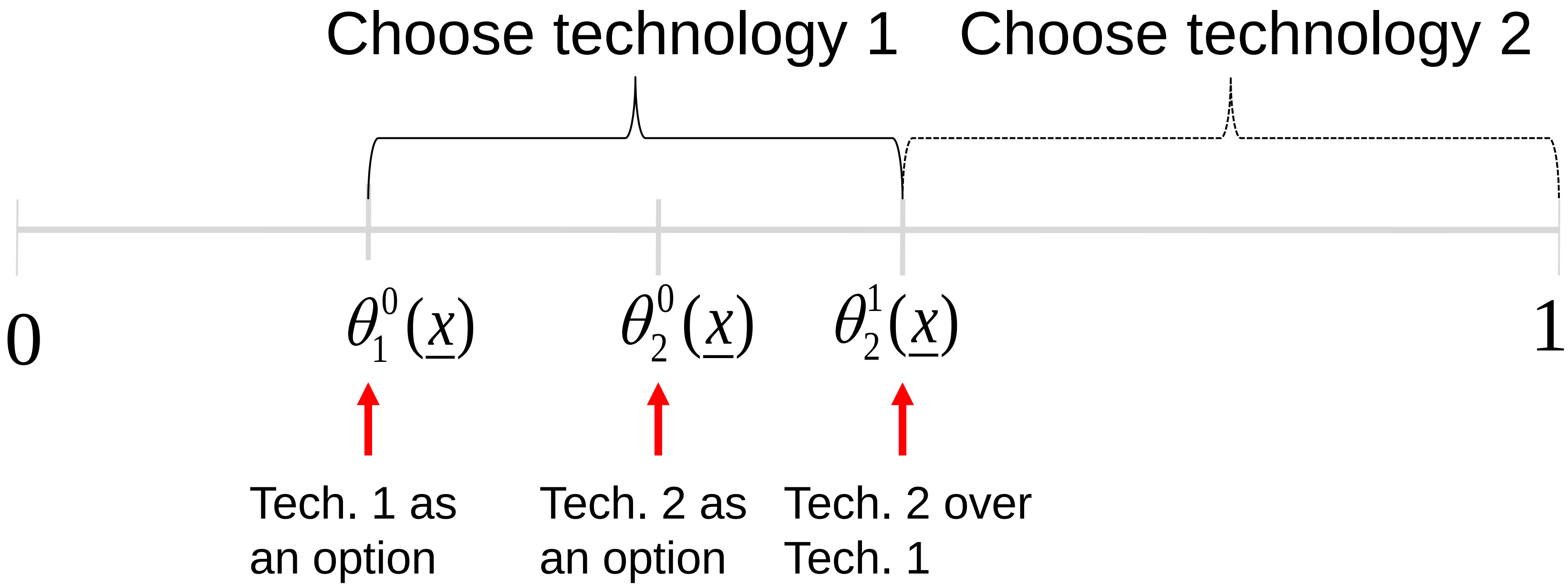
High-def: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- Setting
  - Two video-conf service offerings: Low-def & High-def
    - Low-def has lower price ($p_1 < p_2$), but lower quality ($q_1 < q_2$)
  - Video as an asymmetric technology
    - Encoding is hard, decoding is easy
      - Low-def subscribers could ***display*** high-def signals but not generate them
    - Externality benefits of High-def are higher than those of Low-def ($\beta > 1$)
- Converters characteristics
  - High/Low-def user can decode Low/High-def video signal
  - Simplex, asymmetric, unconstrained
- Users technology choice
  - Best price/quality offering
  - Low-def has lower price but can enjoy High-def quality (if others use it…)

User Decisions

- Decision thresholds associated with *indifference points* for each technology choice: $\theta_1^0(\underline{x}),\ \theta_2^0(\underline{x}),\ \theta_2^1(\underline{x})$
  - $U_1(\theta, \underline{x}) > 0$ if $\theta \geq \theta_1^0(\underline{x})$ - Tech. 1 becomes attractive
  - $U_2(\theta, \underline{x}) > 0$ if $\theta \geq \theta_2^0(\underline{x})$ - Tech. 2 becomes attractive
  - $U_2(\theta, \underline{x}) > U_1(\theta, \underline{x})$ if $\theta \geq \theta_2^1(x)$ - Tech. 2 over Tech. 1
- Which technology would a rational user choose?
  - None if $U_1 < 0,\ U_2 < 0$
  - Technology 1 if $U_1 > 0,\ U_1 > U_2$
  - Technology 2 if $U_2 > 0,\ U_1 < U_2$
- Decisions can/will change as $\underline{x}$ evolves

Sample Configuration



Technology Adoption Model

- Assume a given level of technology penetration $\underline{x}(t)=(x_1(t),x_2(t))$ at time t
  - This translates into an *hypothetical* number of users, $H_i(\underline{x}(t))$, for whom it is rational to adopt technology i at time t (***users can change their mind***)
  - At ***equilibrium***, penetration levels satisfy $H_i(\underline{x}^*) = x_i^*,\ i \in \{1,2\}$
  - For a given $\underline{x}(t)$, expressions for $H_i(\underline{x}(t))$ can be explicitly determined from the users' utility function and decision variables
- From hypothetical to actual decisions: **Adoption dynamics**
  - Not all users learn about the current penetration levels at the same time (information diffuses)
  - Not all users react instantly to information about new penetration levels (rate of adoption in target population)
  - Modeling approach: A diffusion process with constant rate $\gamma < 1$

$$\frac{dx_i(t)}{dt} = \gamma\left(H_i\left(\underline{x}(t)\right) - x_i(t)\right),\ i \in \{1,2\}$$

FROM MODEL TO SOLUTION

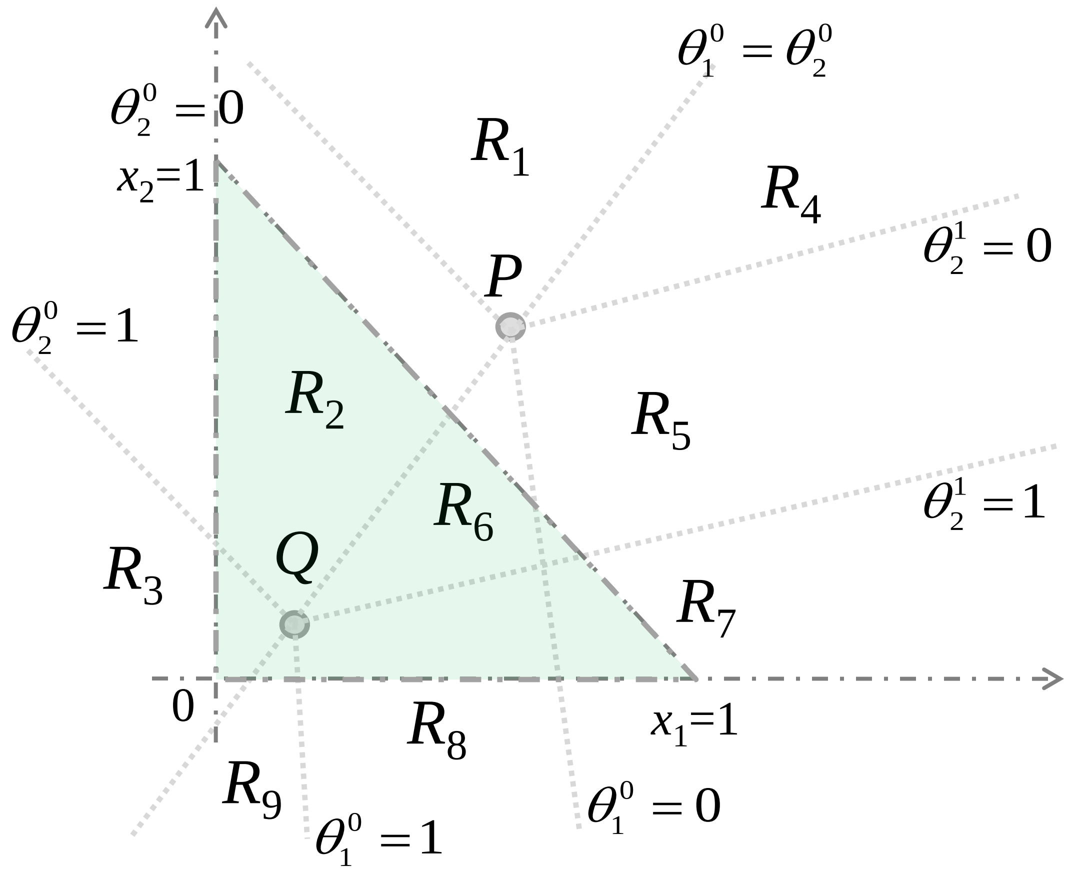
Solving the Model

- It's messy because there are different regions that exhibit different behaviors, and adoption trajectories can cross region boundaries

- But it is solvable and we can compute/characterize
  - All combinations of possible stable (and unstable) equilibria
  - Adoption trajectories in each region
    - Trajectories can be stitched as they cross region boundaries

Identifying "Regions"

- Delineate each region in the (x_1,x_2) plane, where $H_i(\underline{x})$ has a different expression
  - There are ***nine such regions***, i.e., $R_1,\ldots, R_9$
  - They can intersect the feasibility region S $0\leq x_1+x_2\leq 1$ in a variety of ways

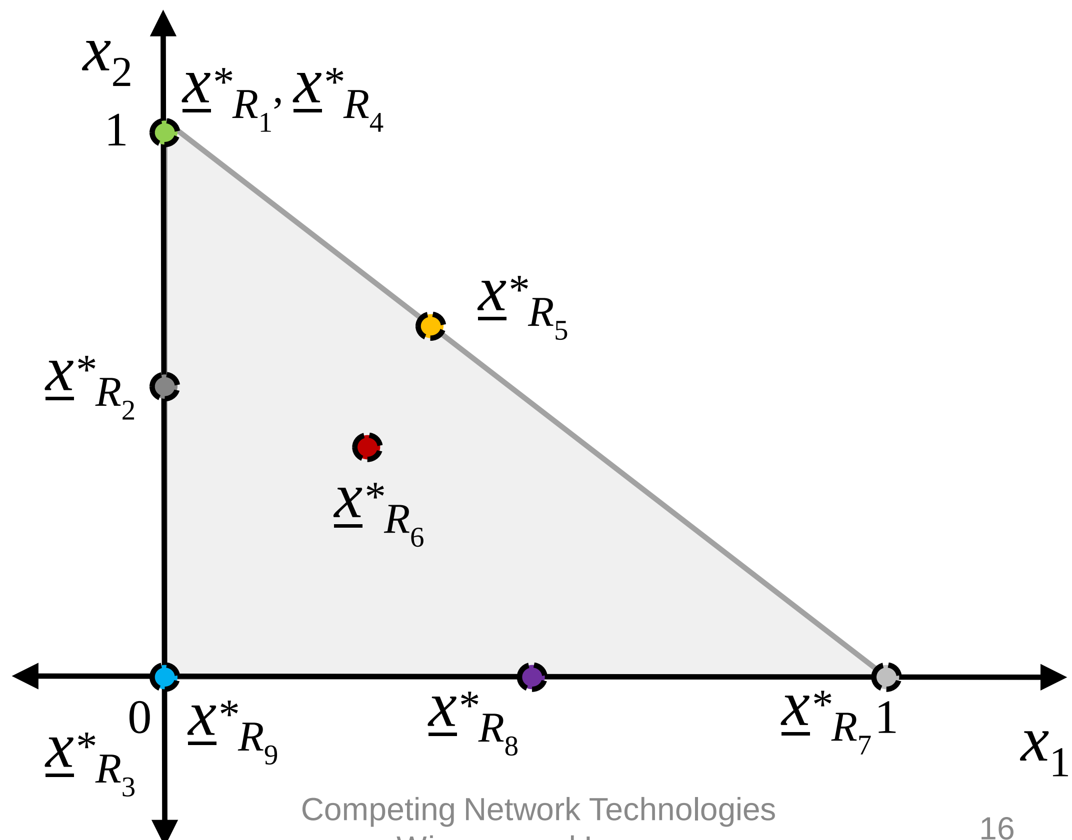


This is in part what makes the analysis complex/tedious

Solving $H_i(\underline{x}^*) = x_i^*$ in Each Region

- Identify "candidate" equilibrium $\underline{x}^*_{R_k}$ in each region R_k
  - Candidates are valid ***only*** if they lie in their region $\left(\underline{x}^*_{R_k} \in R_k \cap S\right)$
  - Equilibria can be stable or unstable

R_i	Candidate $\underline{x}^*_{R_i}$
R_1	$(0,1)$
R_2	$\left(0, \frac{p_2 - q_2}{\beta - q_2}\right)$
R_3	$(0,0)$
R_4	$(0,1)$
R_5	$\left(x^*_{1,R_5}, 1 - x^*_{2,R_5}\right)$
R_6	$\left(x^*_{1,R_6}, x^*_{2,R_6}\right)$
R_7	$(1,0)$
R_8	$\left(\frac{p_1 - q_1}{\beta - q_1}, 0\right)$
R_9	$(0,0)$



Computing Trajectories

- Functional expressions can be computed for each region
  - General expression is of the form

$$x_i(t) = a + be^{-\lambda_1 t} + ce^{-\lambda_2 t}, i \in \{1,2\}$$

    where λ_1 and λ_2 can be positive, negative, or even complex

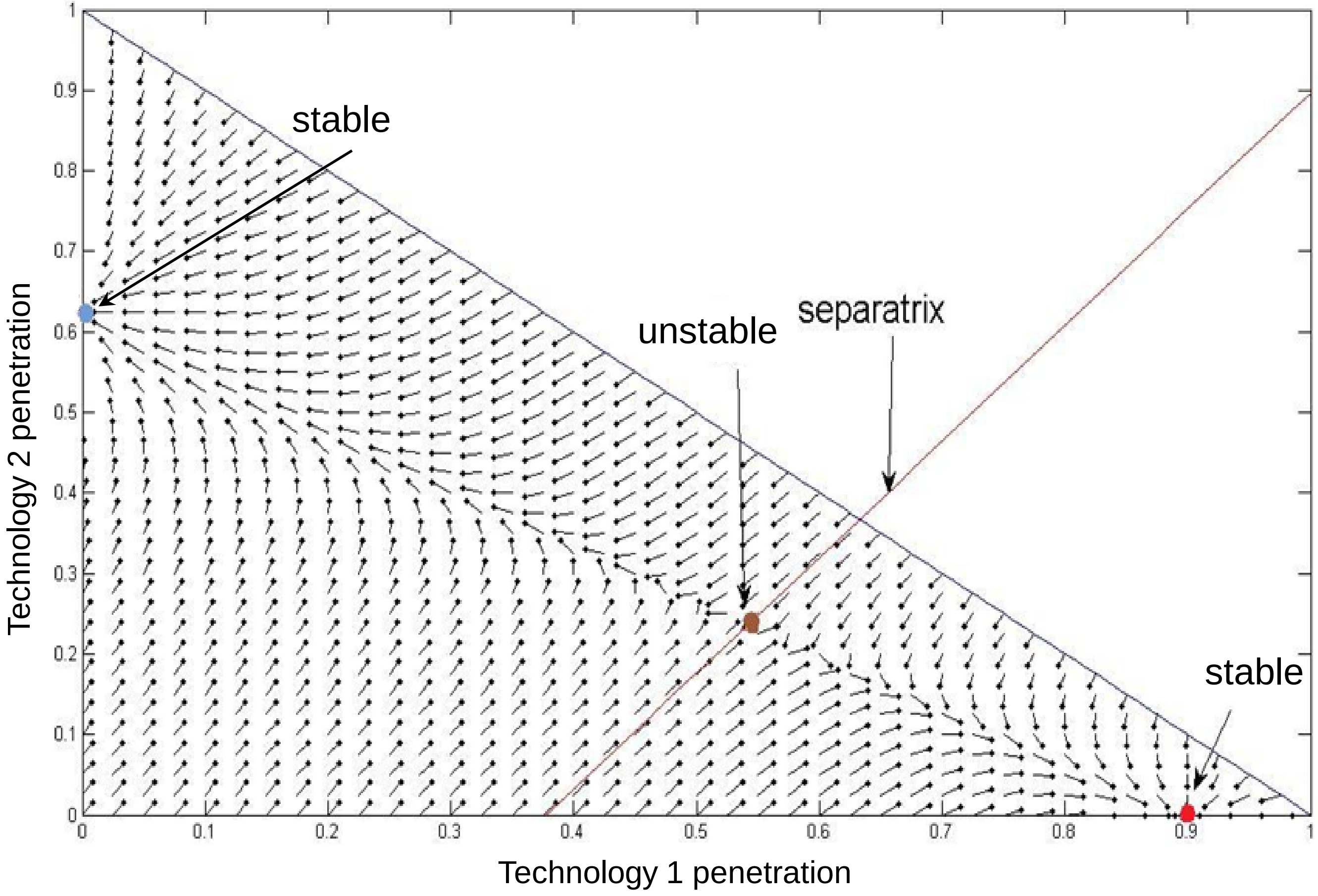
- Trajectories can be stitched together as they cross region boundaries
  - Continuous and continuous derivatives

FROM SOLUTION TO INSIGHT

Key Findings – (1)

1. The system can have at most two stable equilibria
   – Could have had up to three, i.e., Tech. 1 wins, Tech. 2 wins, Tech. 1 and Tech. 2 co-exist
2. In the presence of gateways it is possible for the system ***not to have*** any stable equilibria, and exhibit cyclical adoption trajectories
   – This only happens when $\alpha_1\beta>1$, i.e., Tech. 2 has higher externality benefits and Tech. 1 users can tap into those through gateways/converters, e.g., the video-conf example
   – This ***cannot*** happen in the absence of gateways, i.e., when gateways are absent, technology adoption always converges

A “Typical” Outcome



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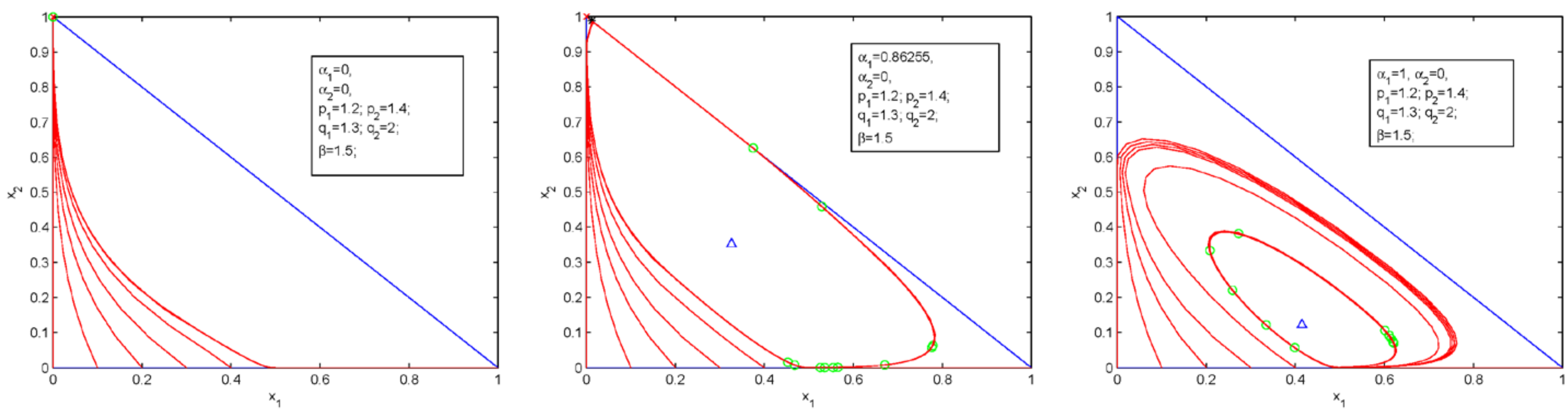
   - This ***cannot*** happen without gateways, i.e., in the absence of gateways, technology adoption always converges

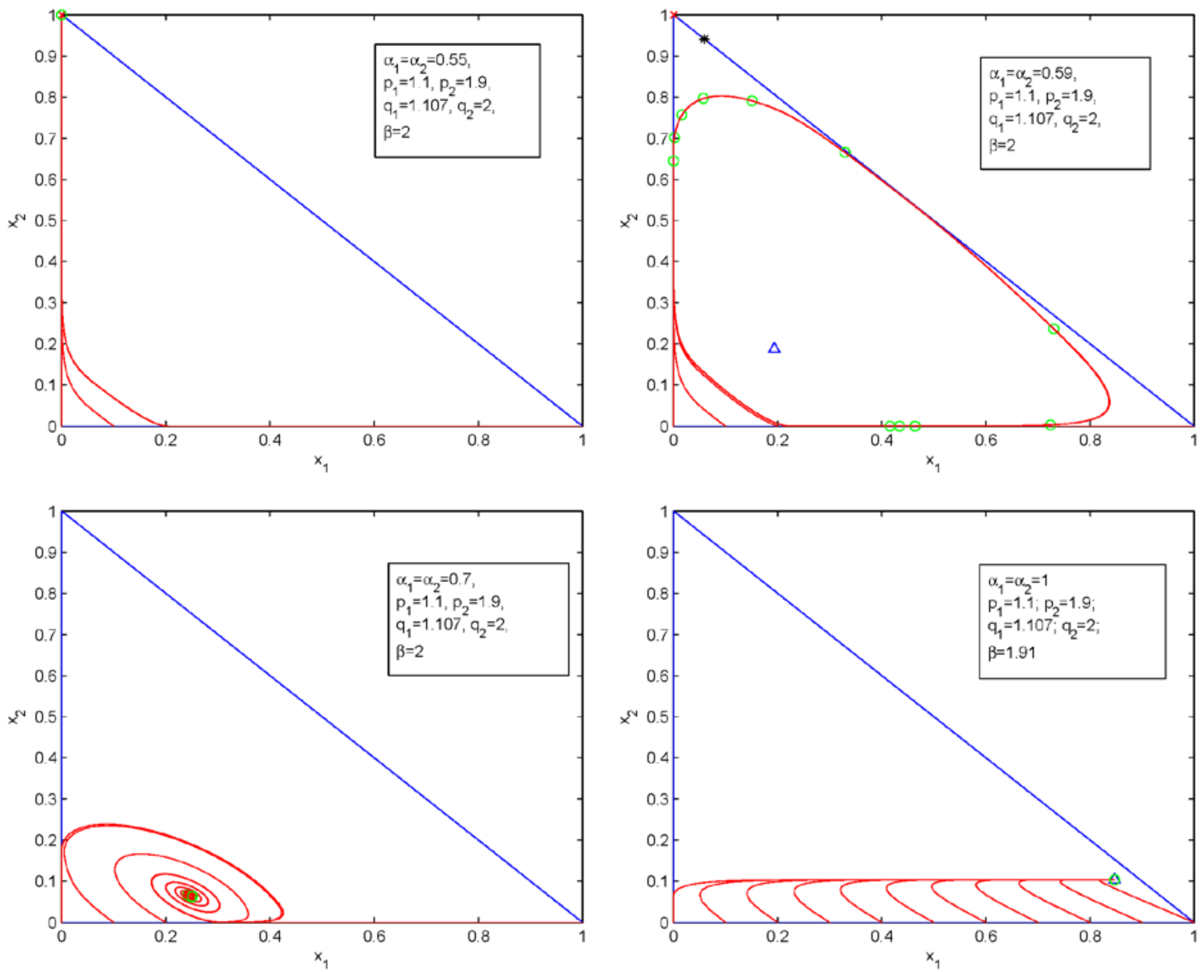
From Stable to Unstable
(Asymmetric Gateways)

- As the efficiency of Tech. 1 gateway increases, system goes from dominance of Tech. 2 to a system with no stable state
  - No stable equilibrium for α_1=1 and α_2=0



From Stable to Unstable to Stable
(Symmetric Gateways)

- No gateways: Tech. 2 captures full market
- Low efficiency gateways: No stable outcome
- Medium efficiency gateways: Neither tech. makes much inroad
- High efficiency gateways: Tech. 1 dominates at close to full market penetration

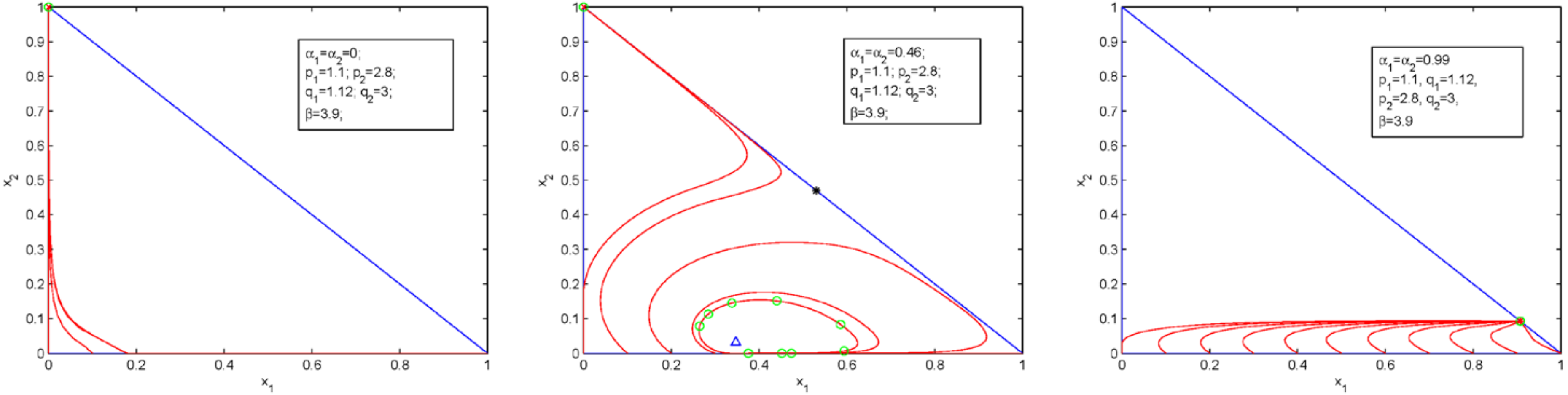


Key Findings – (2)

3. Gateways can help a technology emerge from oblivion and nearly eliminate its competitor
4. Better gateways by either technology or both can hurt overall market penetration
   – This requires $\alpha_1\beta>1$, for Tech. 1, and $\alpha_1\beta<1$ for Tech. 2
5. Tech. 1 can hurt its own and the overall market penetration by introducing or improving its gateways, but Tech. 2 can never hurt its own market penetration through better gateways

From Oblivion to Dominance
(With Intermediate Instabilities)

- Without gateways, Tech. 2 wipes out Tech. 1
- With close to perfect gateways, Tech. 1 nearly wipes out Tech. 2
- Intermediate scenarios can again give rise to permanent market instabilities



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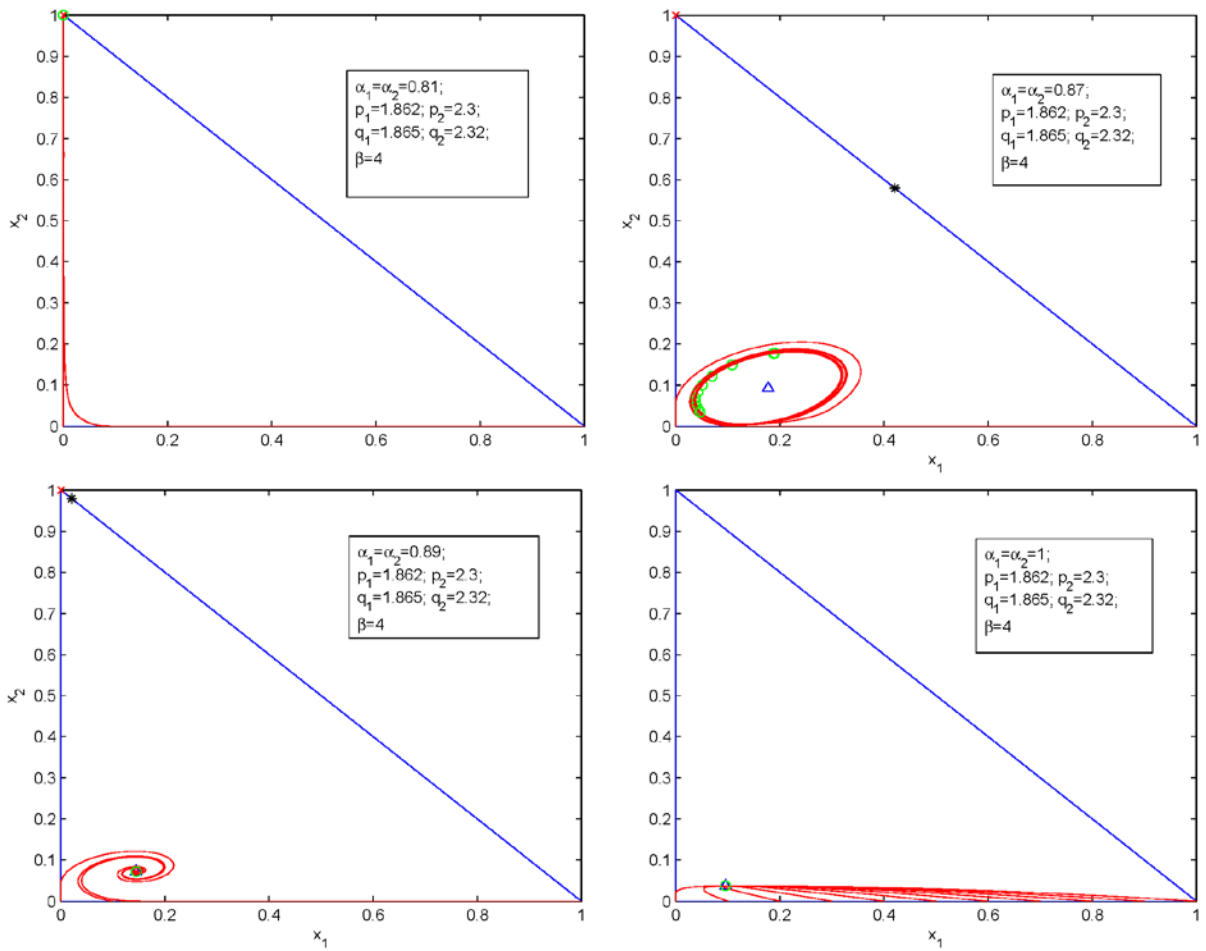
Hurting Overall Market
(Symmetric Gateways)

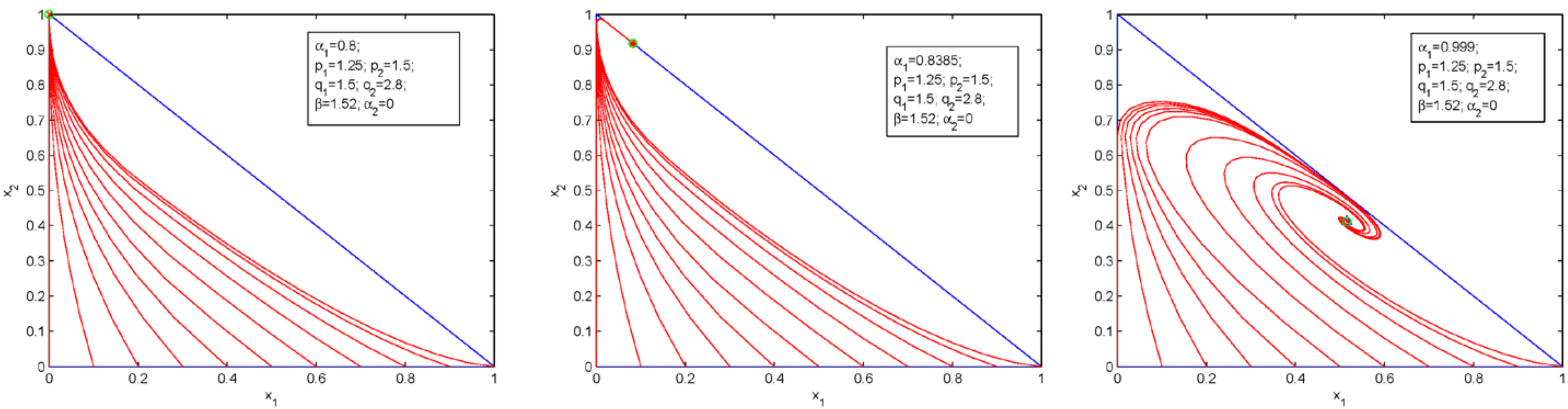
- Better gateways take Tech. 2
  - From 100% market penetration
  - To an unstable market
  - To a combined market penetration with Tech. 1 below 20%!



Hurting Overall Market

(Asymmetric Gateways – Tech. 1)

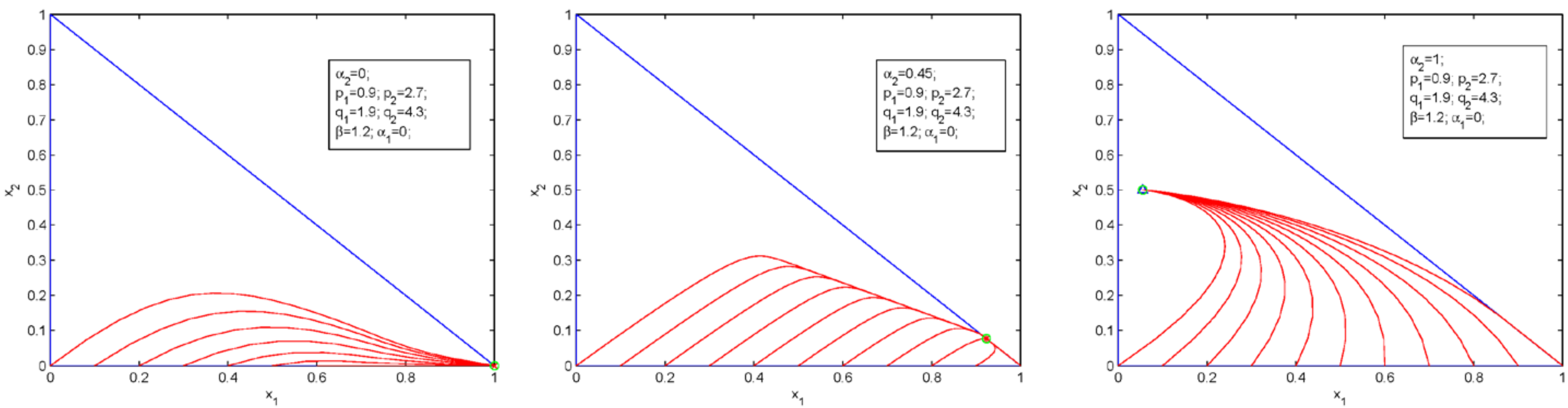
- In the absence of gateways, Tech. 2 takes over the entire market
- Tech. 1 introduces gateways of increasing efficiency
  - Tech. 1 reemerges, but ultimately reduces overall market penetration



Hurting Overall Market

(Asymmetric Gateways – Tech. 2)

- Tech. 2 fails to gain market share without gateways
- Tech. 2 introduces gateways of increasing efficiency
  - Tech. 2 gains market share, but at the cost of a lower overall market penetration



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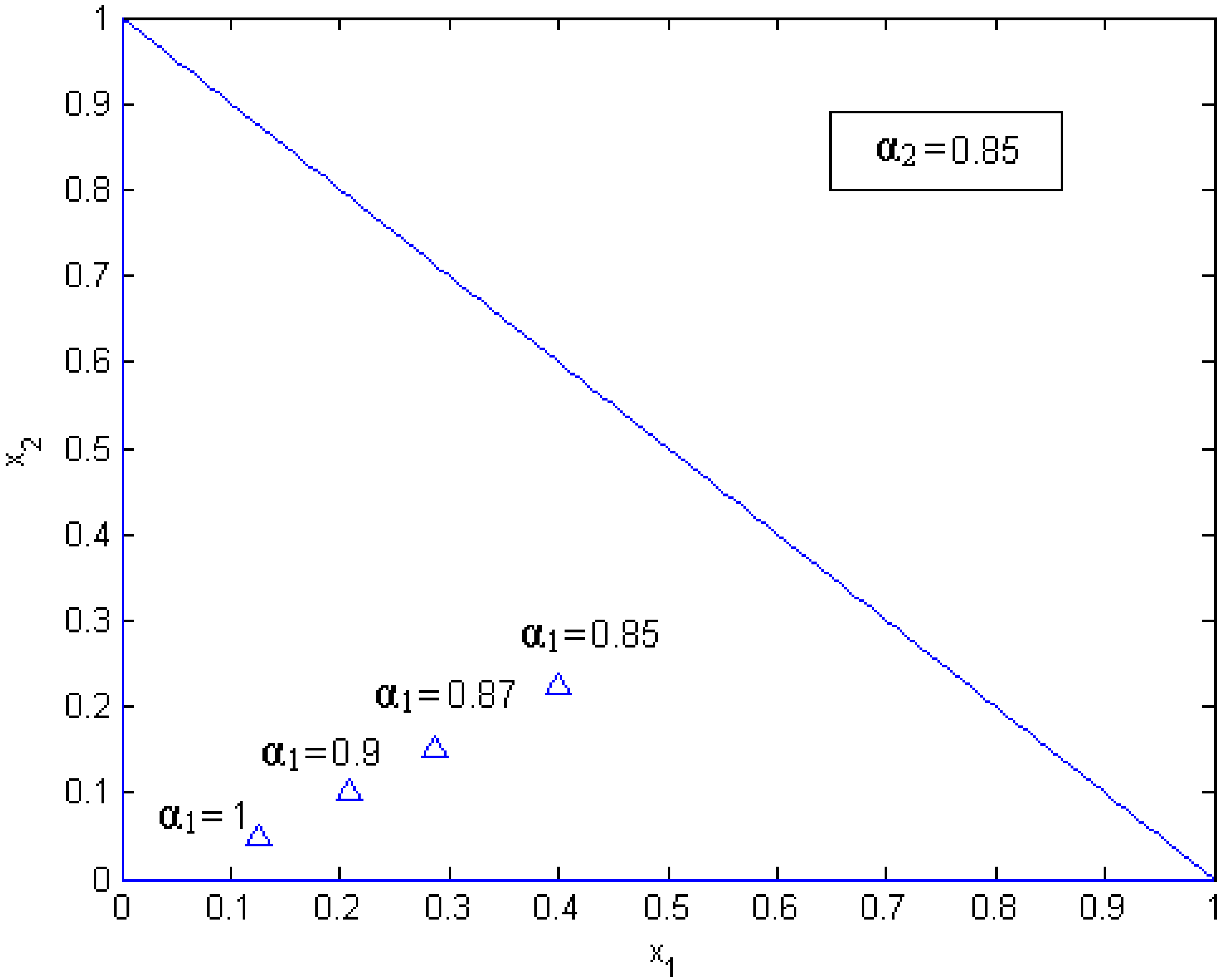
Hurting Tech. 1

(and the Overall Market)



How Robust/Realistic are the Results?

- User preferences (θ)
  - Non-uniform distributions
    - Positively and negatively skewed Beta-distributions
  - Extended to externality benefits
- Different externality models
  - Non-linear externalities
    - Sub-linear: x^{α}, $0<\alpha<1$
    - Super-linear: x^{α}, $\alpha>1$
    - Logarithmic: $\log(x+1)$
  - Pure externalities (no intrinsic technology value)
- No closed-form solutions, but numerical investigations are possible
  - Most/all results hold across all those other settings

Summary

- Gateways can be useful
  - Facilitate technology coexistence and ease adoption of new technologies
  - Allow improved overall market penetration

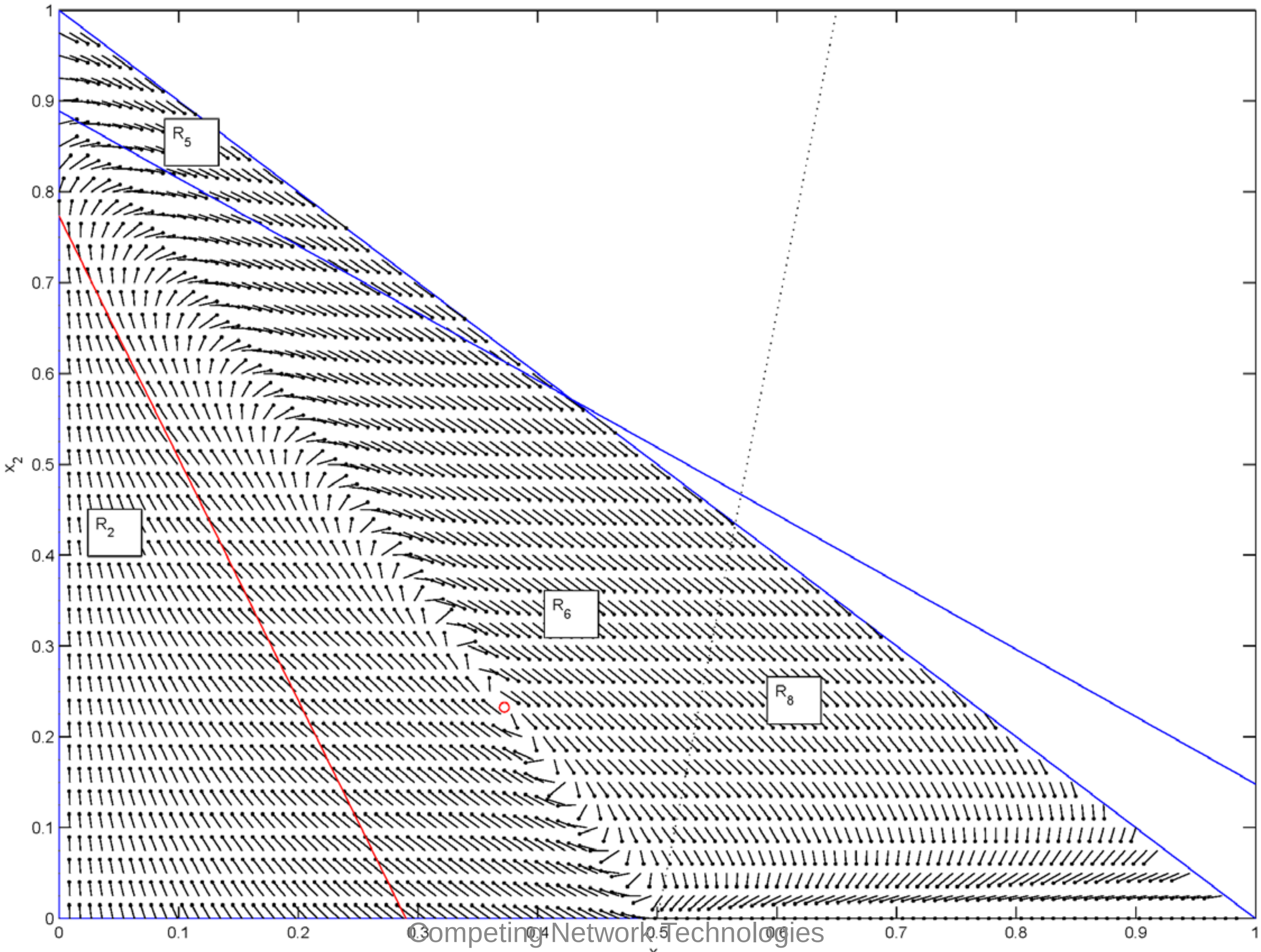
- But they can be harmful too (though mostly in highly asymmetric scenarios – $\alpha_1\beta>1$)
  - Hurt an individual technology (Tech. 1 only)
  - Lower overall market penetration (both technologies)
  - Introduce instabilities (only with large externalities imbalance and unconstrained gateways)

The "good news" though is that harmful effects are largely absent in the context of most "standard" network technologies, e.g., the IPv4-IPv6 transition scenario

- Natural extensions to the investigation
  - Time-varying parameters (price and quality)
  - Strategic policies (dynamic pricing)
  - Incorporate switching costs (likely to require non-trivial model changes)

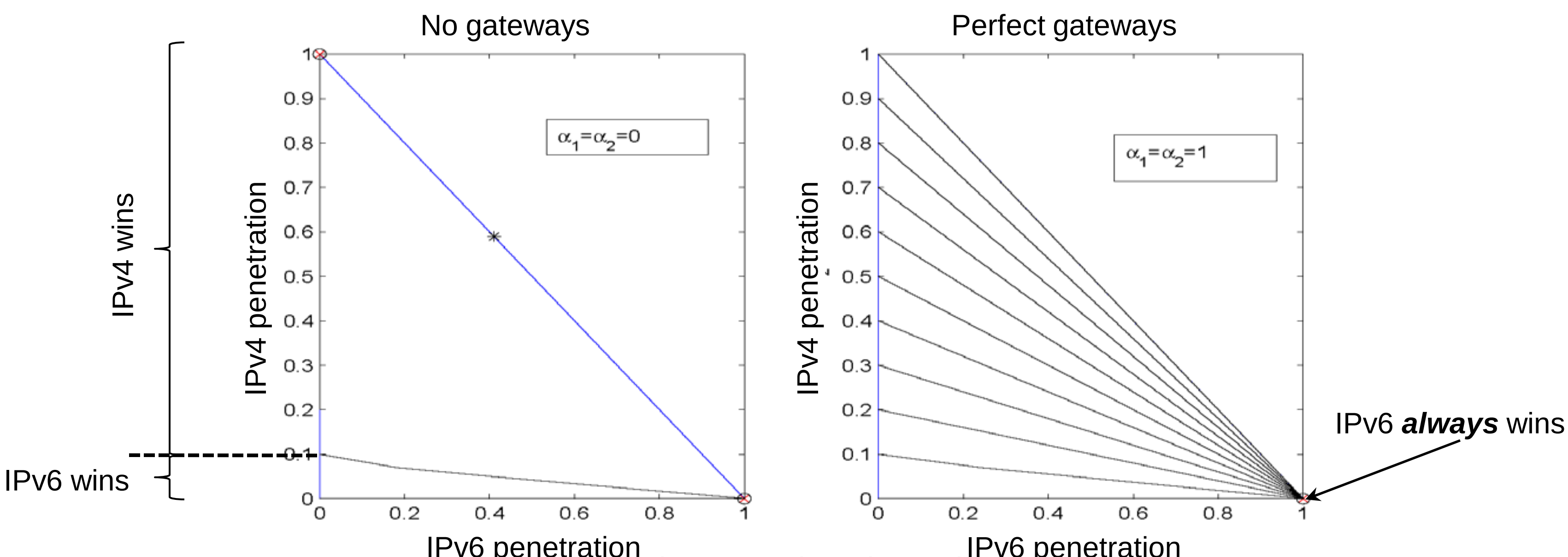
SUPPLEMENTAL MATERIAL

A Closer Look at a "Limit Cycle"



IPv4 Slightly “Better” than IPv6

- In the absence of gateways, IPv6 never takes off unless IPv4 initial penetration is very low…
- After introducing “perfect” gateways (α=100%), IPv6 eventually takes over, irrespective of IPv4 initial penetration
  - There is a “threshold” value (**80%**) for gateway efficiency below which this does not happen!



IPv6 Slightly “Better” than IPv4

- Pretty much the same story
- In the absence of gateways, IPv6 never takes off unless IPv4 initial penetration is very low…
- After introducing “perfect” gateways ($\alpha=100\%$), IPv6 eventually takes over, irrespective of IPv4 initial penetration
  - There is a “threshold” value (**70%**) for gateway efficiency below which this does not happen!