Washington University in St. Louis

Engineering

Overcoming the Challenges of Network Technology Adoption

Roch Guérin

Dept. Comp. Sci. & Eng.

Washington University in St. Louis

Washington

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Acknowledgments

- This talk is based on joint work with Steven Weber and Jaudelice C. de Oliveira from Drexel University

- However, all errors and/or lack of clarity are my own doing

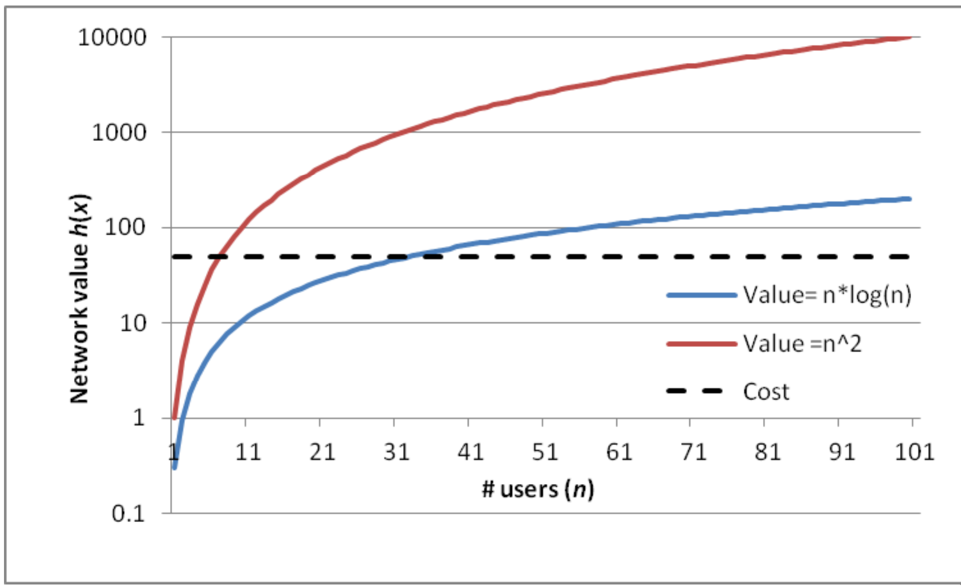
- More details can be found at

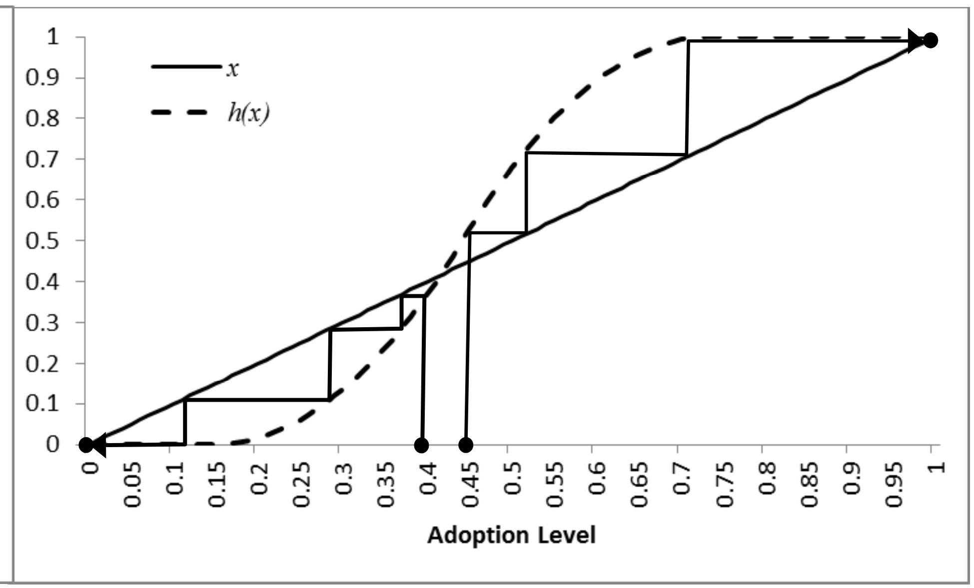
[1] R. Guérin, J. C. de Oliveira, and S. Weber, *"Adoption of bundled services with network externalities and correlated affinities."* To appear in ACM Transactions on Internet Technologies. Early version available on ArXiv, October 2013.

[2] S. Weber and R. Guérin, *"Facilitating adoption of network services with externalities via cost subsidization."* W-PIN+NetEcon Workshop, Austin TX, June 2014. Extended version available on ArXiv

The Adoption Conundrum of Network Technologies

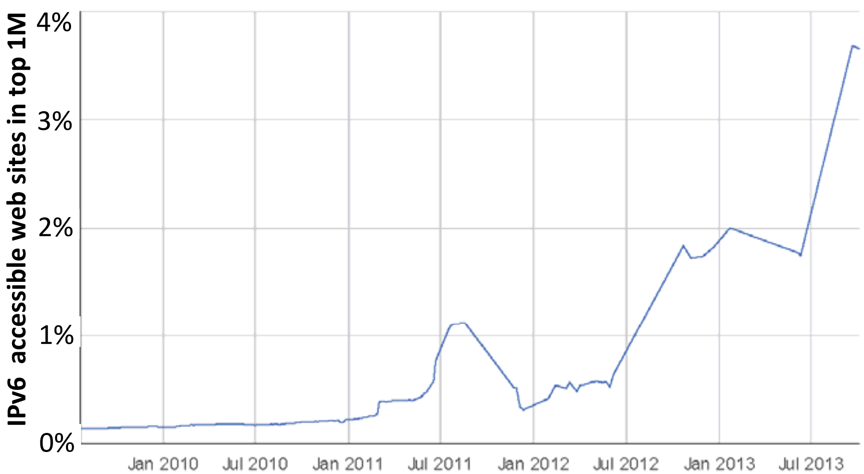
- Useful above a certain adoption threshold, but how to get there?
  - See, *e.g.,* A. Ozment and S. E. Schechter, "Bootstrapping the adoption of Internet security protocols." Proc. WEIS 2006, Cambridge, UK, for a relevant discussion



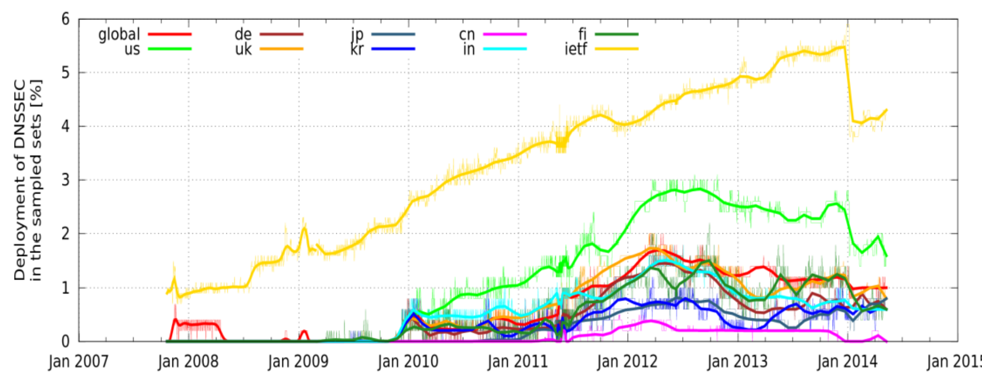


The Adoption Conundrum of Network Technologies

- And there are plenty of examples to illustrate the adoption challenges of network technologies & services



From https://eggert.org/meter/dnssec (sample of ~7300 sites)



- IPv6 standardized circa 1998
- IANA allocates last block in February 2011
- World IPv6 Day in June 2011
- World IPv6 Launch in June 2012
- Still, it took IPv6 15 years to go from 0 to barely 40,000 websites (out of 1M)…

- DNSSEC standard first published in 1999, but updated in 2005, and again in 2008
- Sweden deploys DNSSEC in 2005
- IANA signs the root zone of the DNS in 2010
- Still barely a few % of sites in 2014…

Framing the Problem

- How do we overcome the "chicken-and-egg" adoption dilemma faced by most network technologies and services?
- As alluded to, it is a serious problem that has affected or delayed the success of many network technologies
  - See IAB Workshop on Internet Technology Adoption and Transition (ITAT), Cambridge, UK, December 2013
- Several mechanisms have been proposed to overcome initial adoption hurdles. We focus on two of them
  - ***Bundling***: I like A but don't care too much for B, but will still adopt A+B and in the process help improve B's eventual adoption (demand correlation is key)
  - ***Incentives***: I know that right now there is little value in this new technology, but I'll pay you to adopt it
- Great ideas, but when and how well do they work?

BUNDLING
(OR CAN WE MAKE A WINNER OUT OF TWO LOSERS?)

Bundling For Adoption

- Two relevant bodies of work
  - Product and technology diffusion
  - Product and service bundling
- Much work in marketing research on diffusion of products with externalities
  - Clear focus on adoption (dynamics and at equilibrium), but
  - Little or no work accounting for the impact of bundling
- Investigation of bundling strategies
  - Focus on optimal pricing strategies (to maximize revenue, not adoption)
  - Accounts for demand correlation (highlights the benefit of negative correlation)
  - Until recently, externalities were absent from these models
  - Three recent works have explored bundling with externalities
    - All three focus on optimal pricing and assume independent demands, *i.e.,* no correlation in the values users assign to different products

Setting Things Up
(as simply as possible)

- Modeling individual adoption decisions based on *utility functions*

$$V_i(x_i(t)) = U_i + e_i x_i(t) - c_i, \text{ where}$$

  - U_i is the user's (random) valuation for technology i (follows a certain distribution)
  - e_i is the strength of technology i's externality factor (how value increases with adoption)
  - $x_i(t)$ is the level of adoption of technology i at time t (varies from 0 to 1)
  - c_i is the adoption "cost" of technology i (resources, training, upgrades, acquisition, etc.)
- Adoption $\Leftrightarrow V_i(x_i(t))>0$, with equilibria such that $h_i(x_i^*)=x_i^*$, where $h_i(x)=P(U_i>c_i-e_i x_i)$
  - Rational users want to see positive utility from adopting
  - Equilibria when # adopters exactly matches # users with positive utility
- When bundling two technologies (1 and 2), the bundle's utility $V(x(t))$ is of the form

$$V(x(t)) = U + ex(t) - c$$

  - Where† $U = U_1+U_2$, $e = e_1+e_2$, $c = c_1+c_2$, and $x(t)$ is the bundle's adoption level at time t

The question is "**When is $x^* \geq \max\{x_1^*, x_2^*\}$?,**" *i.e.,* can we get Win-Win outcomes? And what role does the *joint distribution* $F(U_1,U_2)$; in particular correlation, play?

† Can be generalized to account for complements/substitutes and (dis)economies of scope

Capturing the Effect of Correlation

- Accounting for correlation involves two main parameters
  1. Individual (marginal) distributions of users' technology valuation
  2. Specification of the joint distribution of technology valuations
     - Copulas offer a standard approach to realize a parametrized joint distribution with known marginals, though often with limitations on the range of feasible correlation coefficients
- A general solution is possible but analytically challenging (and opaque, *i.e.*, does not yield any real insight), even for simple marginals, *e.g.,* uniform distribution
- We can, however, explicitly solve for special cases
  - Uniform distributions and perfect negative/positive correlation
    - Helps identify instances of Win-Win (WW) and Lose-Lose (LL) outcomes
  - Discrete distribution
    - Allows for the systematic investigation of the impact of correlation (ρ)

Two Extreme Scenarios

- Users' valuation U for both technology 1 and 2 is uniformly distributed in [0,1]
  - Opposite correlation scenarios ($\rho = +1$ and -1)
    - $\rho = +1$: All user likes both technologies equally
    - $\rho = -1$: A user that assigns value u_i to technology i, assigns value $1\text{-}u_i$ to the other
- Bundled offering: $V(x(t))=(U_1+U_2)+(e_1+e_2)x(t)-(c_1+c_2)$
  - $\rho = +1$: Bundle adoption is as for individual technologies but with "rescaling"
    - $U + (e/2)x(t) - (c/2) > 0$, where U has the same uniform distribution as U_1 and U_2
  - $\rho = -1$: Bundle adoption depends solely on cost and average bundle value M
    - $V(x(t)) = M + ex(t) - c$, so that everyone (no one) adopts at $t = 0$ iff $c < M$ ($c \geq M$)

Clearly correlation in technology valuation plays a role

Focusing on the Case $\rho = 1$

- **WW** outcomes:
  - Combinations of low-cost, low externality and high-cost, high externality technologies
- No **LL** outcomes (in this particular configuration)

			0	$\frac{2-c}{2-e}$	1
			$c > 2$	$e < c < 2$	$c < e \wedge 2$
$(0,0)$	$c_1 > 1$	$c_2 > 1$	SS True	WW False	WW False
$\left(0, \frac{1-c_2}{1-e_2}\right)$	$c_1 > 1$	$e_2 < c_2 < 1$	SL	WL or WW	WW
$(0,1)$	$c_1 > 1$	$c_2 < e_2 \wedge 1$	SL	WL	WS
$\left(\frac{1-c_1}{1-e_1}, 0\right)$	$e_1 < c_1 < 1$	$c_2 > 1$	LS	LW or WW	WW
$(1,0)$	$c_1 < e_1 \wedge 1$	$c_2 > 1$	LS	LW	SW
$\left(\frac{1-c_1}{1-e_1}, \frac{1-c_2}{1-e_2}\right)$	$e_1 < c_1 < 1$	$e_2 < c_2 < 1$	LL False	WL or LW	WW False
$\left(\frac{1-c_1}{1-e_1}, 1\right)$	$e_1 < c_1 < 1$	$c_2 < e_2 \wedge 1$	LL False	WL	WS
$\left(1, \frac{1-c_2}{1-e_2}\right)$	$c_1 < e_1 \wedge 1$	$e_2 < c_2 < 1$	LL False	LW	SW
$(1,1)$	$c_1 < e_1 \wedge 1$	$c_2 < e_2 \wedge 1$	LL False	LL False	SS True

Exploring Things Further
A Basic Discrete Scenario

- Technology valuations take only two possible discrete values
  - Like ($U_i = 1$) and Don't Like ($U_i = 0$)
  - Users are equally likely to like or not like a technology ($P[U_i=1]=P[U_i=0]=1/2$), with their joint distribution parametrized by $p \in [0,1]$

$U_1 \setminus U_2$	0	1	
0	$(1-p)/2$	$p/2$	1/2
1	$p/2$	$(1-p)/2$	1/2
	1/2	1/2	

  - Correlation coefficient $\rho = 1 - 2p$ goes from −1 to +1 as p varies in [0,1]
- Main benefit is that both separate and bundle equilibria can now be characterized as a function of ρ

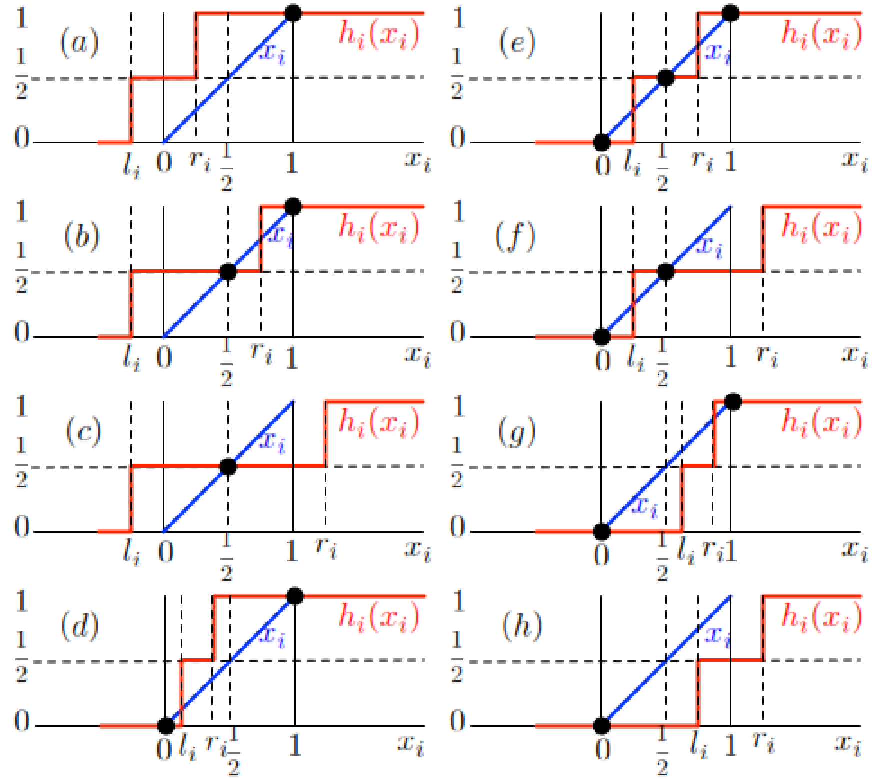
Equilibria Under Discrete Valuations

- **Separate equilibria**

  $l_i = (c_i - 1)/e_i$ and $r_i = c_i/e_i$

- Three possible equilibria

  0, 1/2, and 1

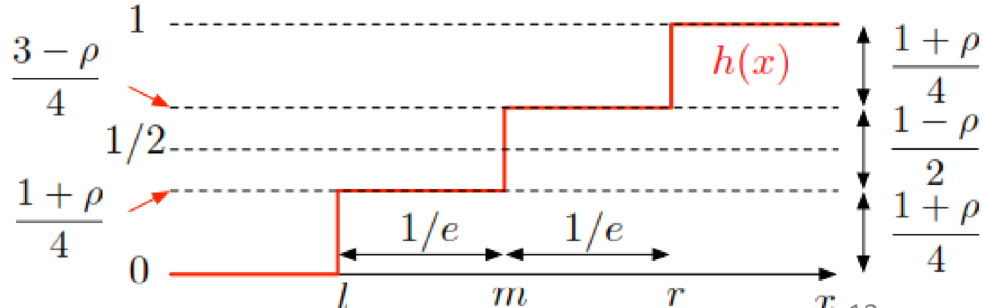


- **Bundle equilibria**

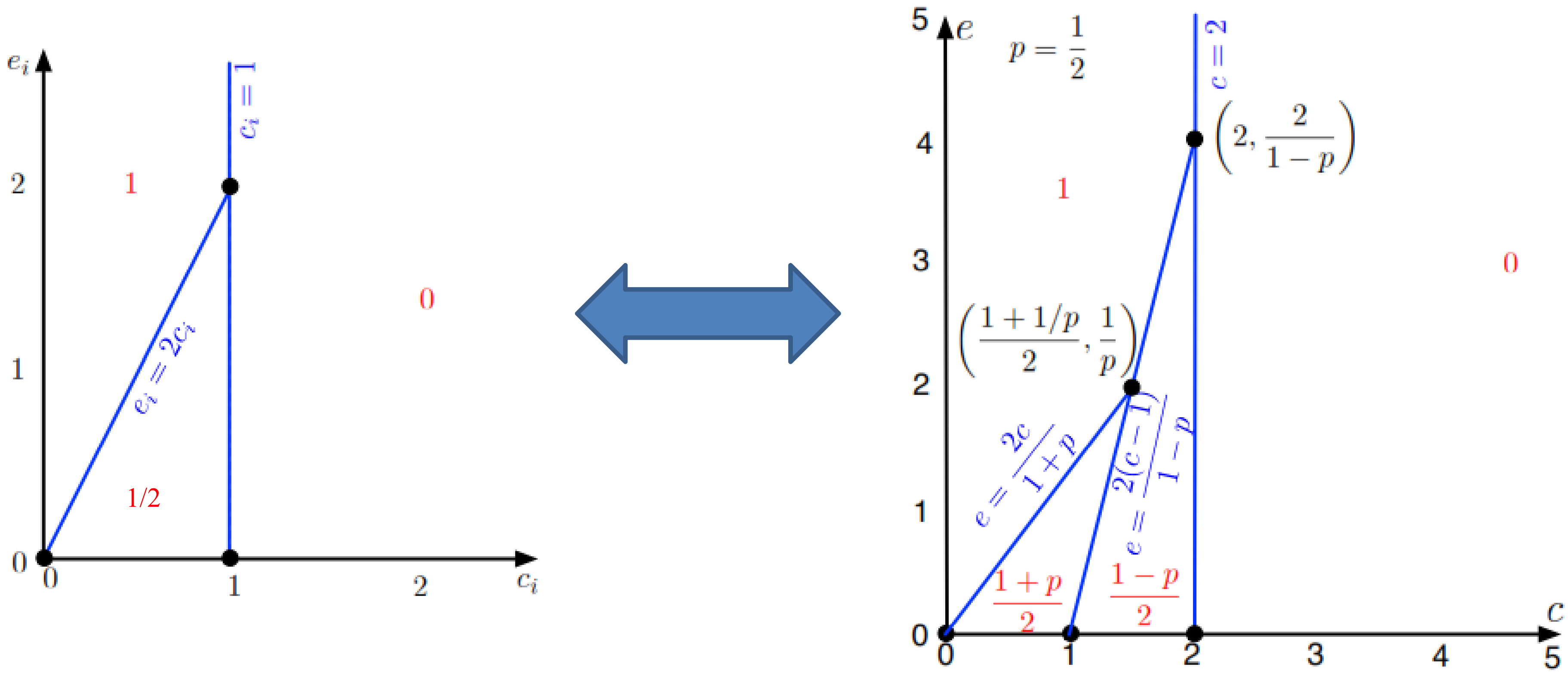
  $l = (c - 2)/e$, $m = (c - 1)/e$, and $r = c/e$

- 3 possible equilibria:

  0, $(1 + \rho)/4$, $(3 - \rho)/4$, and 1



A Pictorial View of When (and Why) Bundling Can Help?

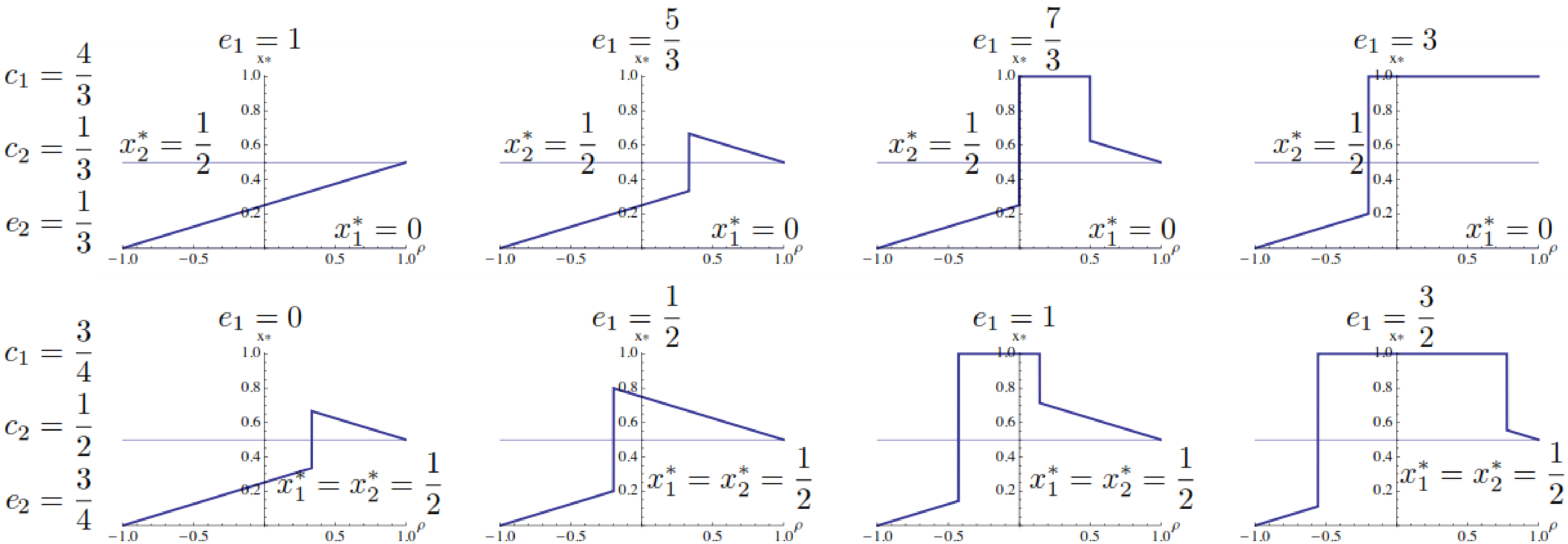


Both *WW* and *LL* Outcomes

SepEq		BundleEq	0	$\frac{1+\rho}{4}$	$\frac{3-\rho}{4}$	1
SepEq	SepEq conditions ⇓	BundleEq conditions ⇒	$c > 2$	$c < 2$ $(1+\rho)e < 4(c-1)$	$c < 2$ $(1+\rho)e > 4(c-1)$ $(3-\rho)e < 4c$	$c < 2$ $(1+\rho)e > 4(c-1)$ $(3-\rho)e > 4c$
$(0,0)$	$c_1 > 1$	$c_2 > 1$	SS True	WW False	WW False	WW False
$(0,1/2)$	$c_1 > 1$	$c_2 < 1$ $e_2 < 2c_2$	SL	WL	WW	WW
$(0,1)$	$c_1 > 1$	$c_2 < 1$ $e_2 > 2c_2$	SL	WL	WL	WS
$(1/2,0)$	$c_1 < 1$ $e_1 < 2c_1$	$c_2 > 1$	LS	LW	WW	WW
$(1,0)$	$c_1 < 1$ $e_1 > 2c_1$	$c_2 > 1$	LS	LW	LW	SW
$(1/2,1/2)$	$c_1 < 1$ $e_1 < 2c_1$	$c_2 < 1$ $e_2 < 2c_2$	LL False	LL	WW	WW
$(1/2,1)$	$c_1 < 1$ $e_1 < 2c_1$	$c_2 < 1$ $e_2 > 2c_2$	LL False	LL	WL	WS
$(1,1/2)$	$c_1 < 1$ $e_1 > 2c_1$	$c_2 < 1$ $e_2 < 2c_1$	LL False	LL	LW	SW
$(1,1)$	$c_1 < 1$ $e_1 > 2c_1$	$c_2 < 1$ $e_2 > 2c_1$	LL False	LL	LL False	SS

- WW outcomes:
  1. As before: Cheap, low externality + Expensive, high externality
  2. But also combining two "middling" technologies
- LL outcomes:
  – Typically for highly negative correlation, *i.e.*, $\rho \approx -1$

Illustrating the Impact of ρ (Case 1)



For WW outcomes: Choose technologies that are

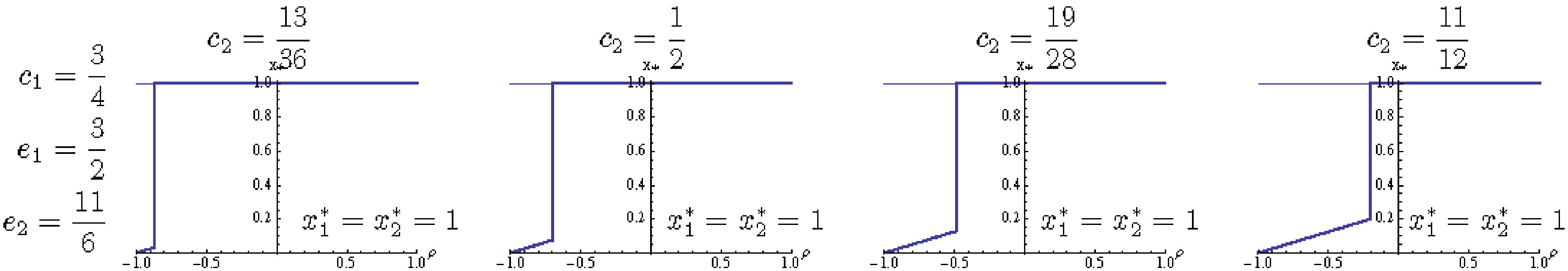
1. (a) either heterogeneous in cost-benefit structure

   (b) or average (in cost & externality)

2. Sufficiently correlated in user valuations, **<u>but not too much</u>**!

√ We know

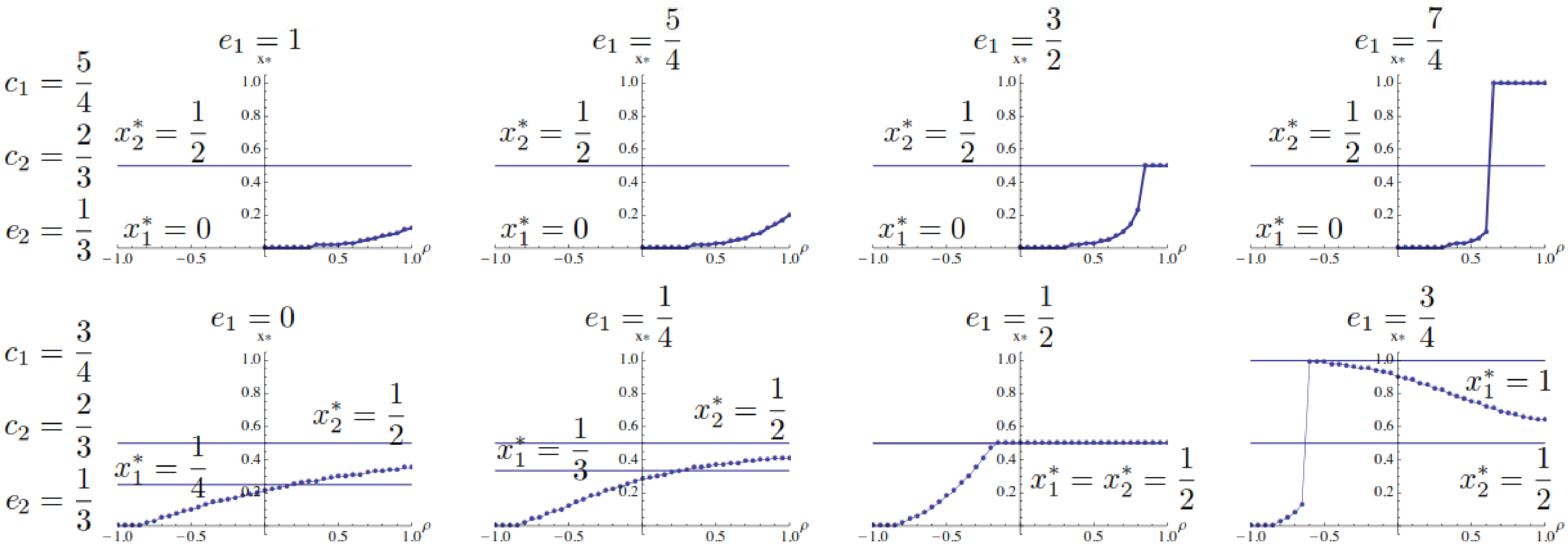
Illustrating the Impact of ρ (Case 2)



LL outcomes can arise when valuation correlation is negative enough

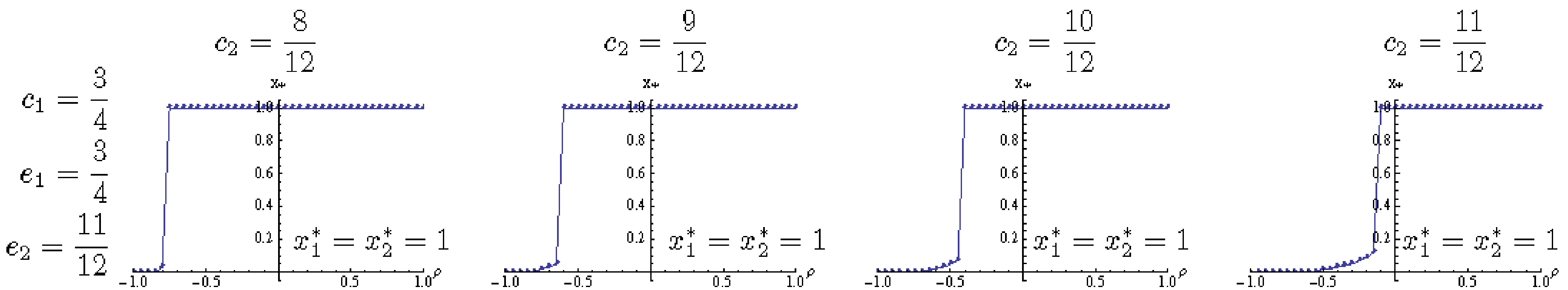
- Negative correlation means that few users like both services
- Can prevent early adoption phase to reach critical mass, *i.e.*, past the adoption level for which externality can start fueling continued adoption growth

Limited Robustness Test
Back to the Uniform Distribution – (1)



- WW outcomes qualitatively similar in behavior
  - Correlation must exceed a threshold
  - Exceeding that threshold can be harmful

Limited Robustness Test
Back to the Uniform Distribution – (2)



- LL outcomes also yield qualitatively similar behaviors
  - Arise mostly for negative correlation

SUBSIDIES
(PAYING TODAY FOR TOMORROW'S WINNERS)

Offering Incentives to Early Adopters

- When using subsidies, two key questions are
  1. How big should the subsidy be?
  2. How long should subsidies be offered?
- And the goals are typically to
  1. Improve/maximize final adoption (after subsidies stop)
  2. Minimize total cost of subsidies
  3. And to a lesser extent, minimize total duration of subsidies
- Addressing those issues calls for not only understanding adoption decisions, but also their dynamics

A Basic Model

- As for bundling, adoption decisions are based on a user's utility function: $V(x(t)) = U + ex(t) - c + s(t,x(t))$, where as before
  - U is the user's (random) valuation for the technology
  - e is the strength of the technology externality
  - $x(t)$ is the level of adoption of the technology at time t
  - c is the adoption "cost" of the technology
  - $s(t,x(t))$ is the subsidy level at time t (it can depend on $x(t)$)
- Adoption dynamics are captured through a standard diffusion model

  $\dot{x}(t) = \gamma\left(P[V(x(t)] - x(t)\right), \gamma > 0$, *i.e.,* the rate of change in adoption is proportional to the difference between the fraction of users who *would adopt* given an adoption level of $x(t)$, and those who *have* adopted
- For simplicity we focus on the simplest type of subsidies, *i.e.,* equal to a constant value s for a given period of time $[t_0, T]$ and 0 otherwise

Understanding Adoption Equilibria and Dynamics

- Equilibria verify $\dot{x}(t) = 0$ (or $x(t) = 0$ with $\dot{x}(t)|_{x=0} \leq 0$, and $x(t) = 1$ with $\dot{x}(t)|_{x=1} \geq 0$)
- Since subsidies eventually stop, the system will ultimately settle to one of the feasible equilibria under no subsidy
  - So characterizing possible adoption equilibria in the absence of subsidies is a useful first step
  - For simplicity, we focus on the case where user valuations are uniformly distributed in $[u_m, u_M]$

Adoption Equilibria & Dynamics Without Subsidies

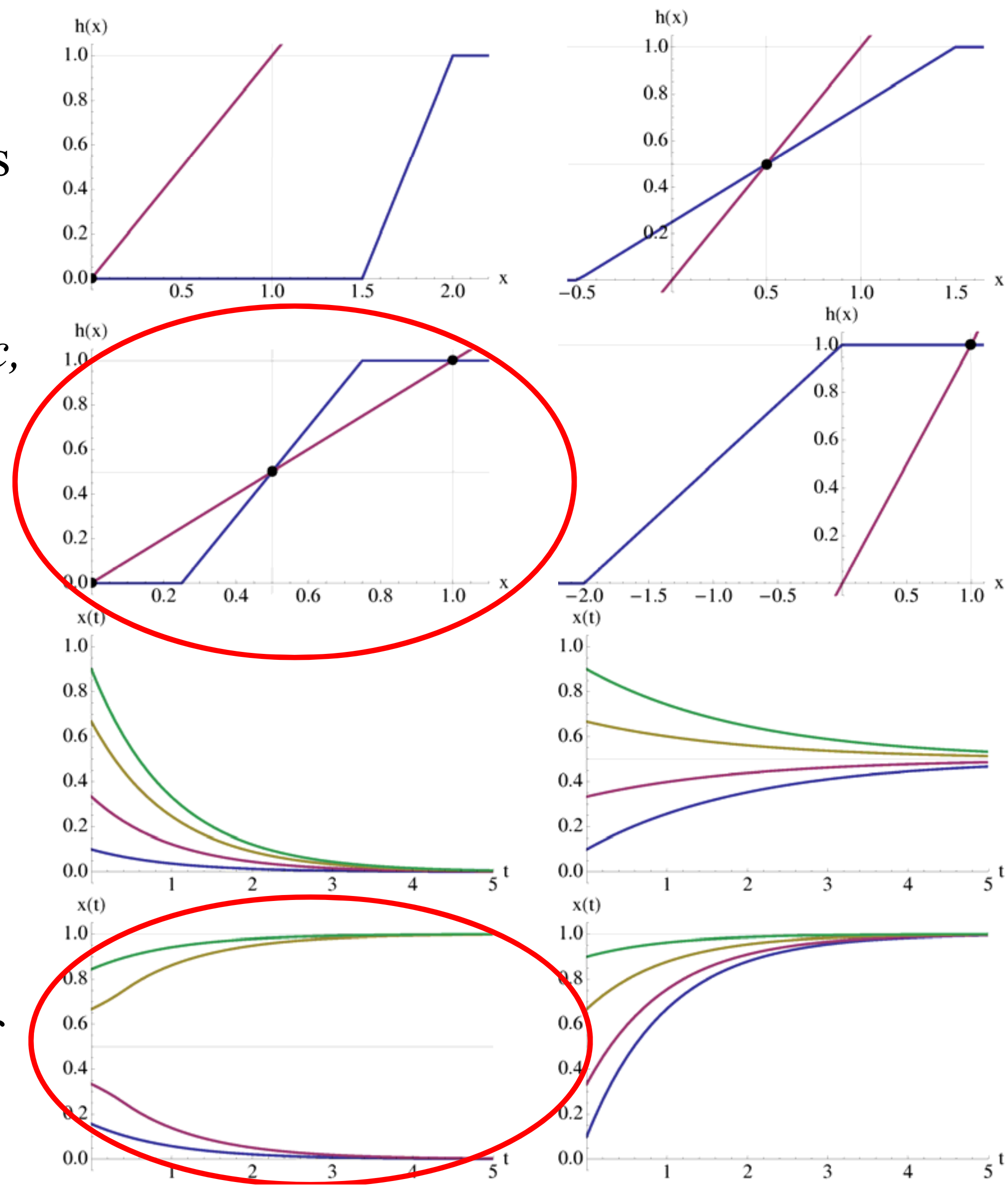
- Equilibria and adoption dynamics can be shown to belong to four possible configurations based on the relationship between u_m, u_M, c, and e, with one possible internal equilibrium of the form

  $$x^{o}(c) = (u_M - c)/(u_M - (u_m - c))$$

- The most interesting regime is when

  $$u_M < c < u_m + e$$

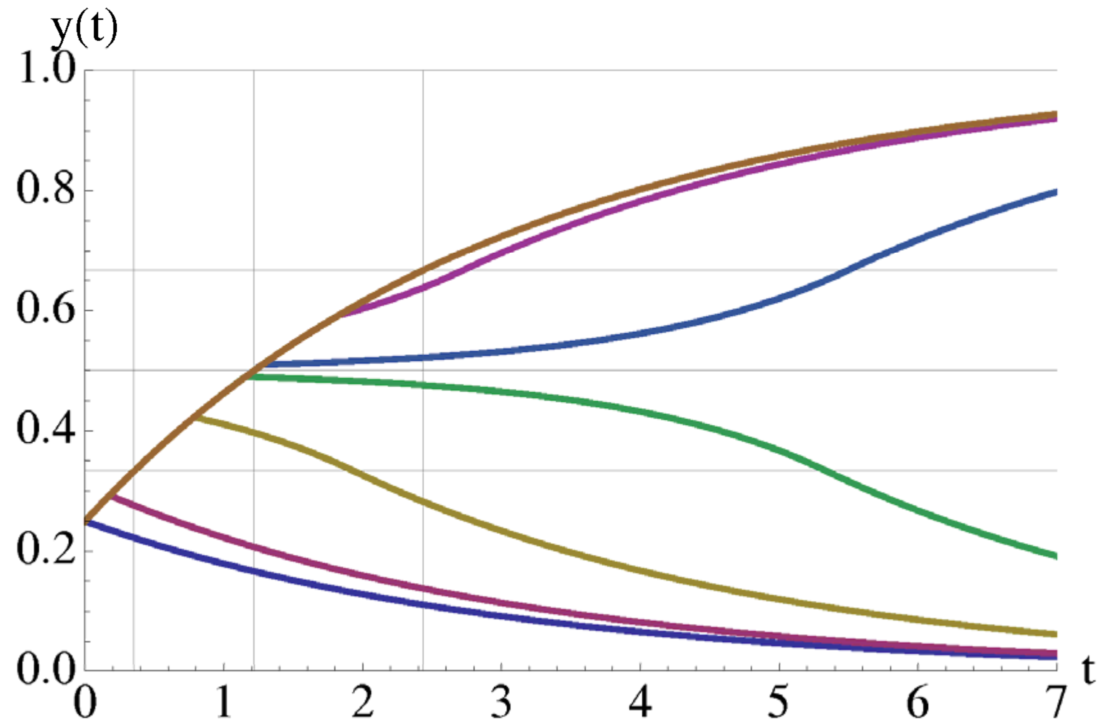
  In this scenario, $x^{o}(c)$ is and unstable equilibrium that demarcates the stability region of the two stable equilibria 0 and 1



Adoption Equilibria & Dynamics With Subsidies

- Consider first a special case
  - Full subsidy: $s = c$ for a period of duration T^{o}_{FS}, *i.e.*, until adoption exceeds $x^{o}(c)$ starting from $x(0)=0$

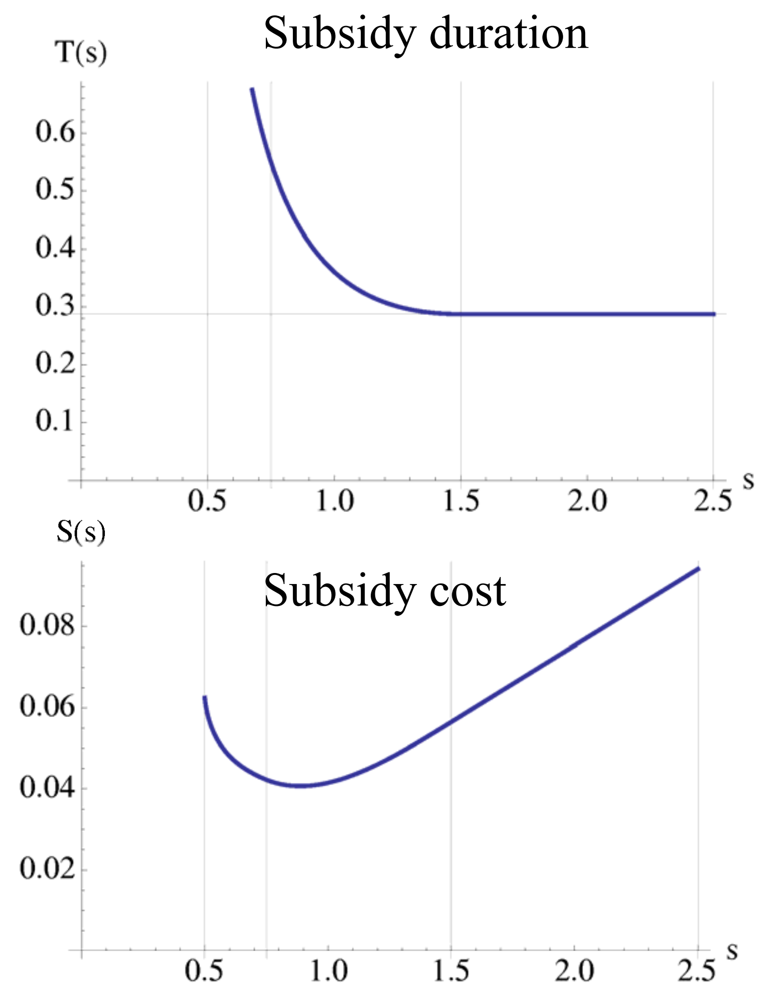
$$T_{FS}^{o} = \frac{1}{\gamma}\log\left(\frac{1}{1-x^{o}(c)}\right)$$



Different outcomes as a function of subsidy duration

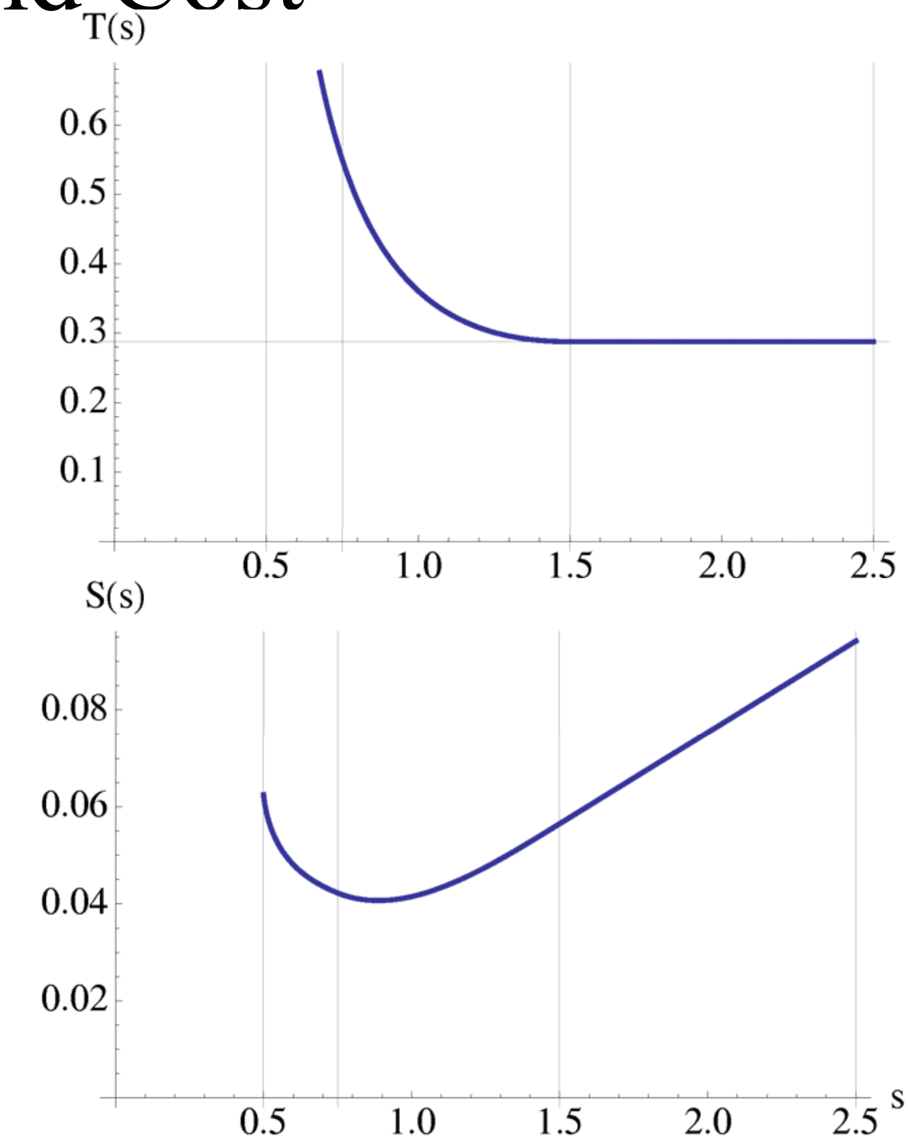
Subsidy Duration and Cost

- General case with subsidy of s until an adoption level of $x^o(c)$ is reached, starting again from $x(0)=0$
- Both minimum subsidy duration $T(s)$ and resulting subsidy $S(s)$ cost can be characterized as a function of s
- Of interest is the fact that subsidy cost has a minimum value



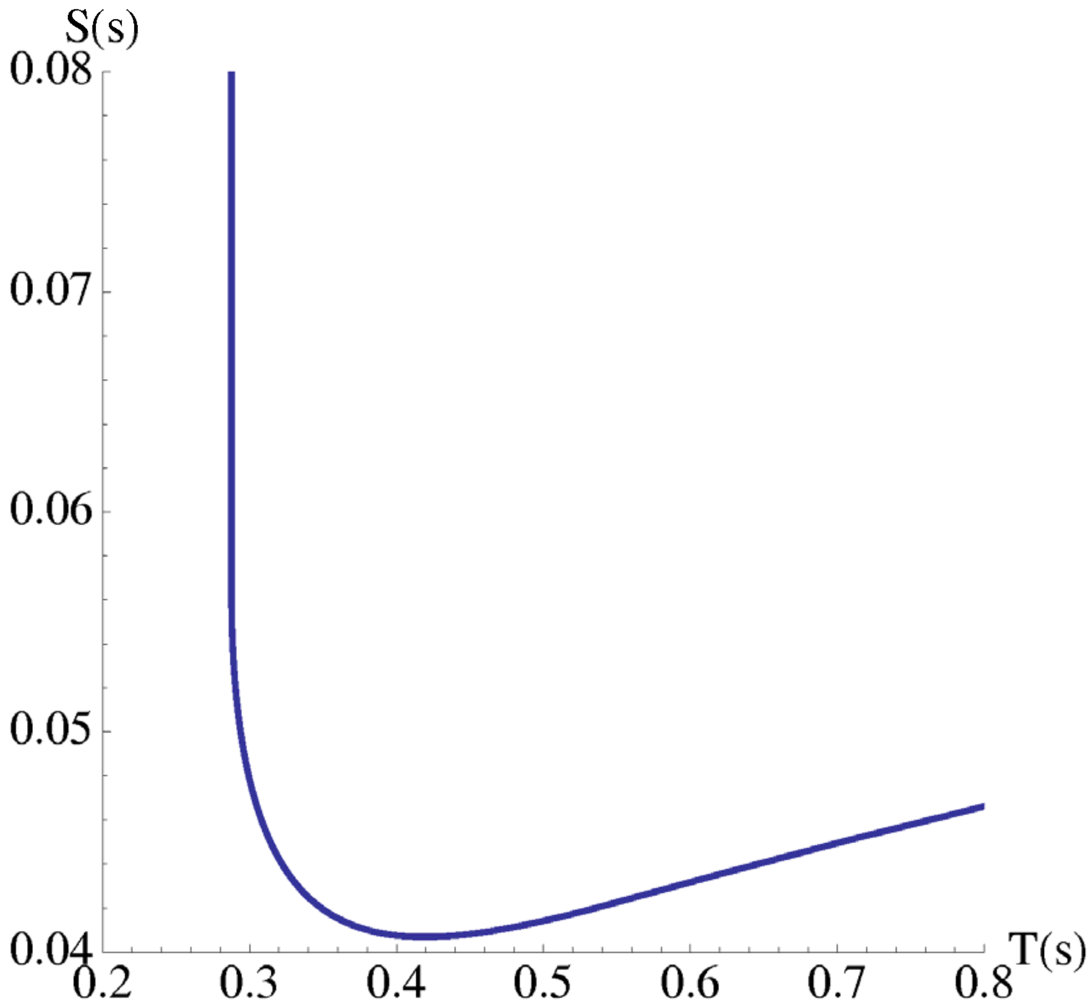
Trade-Off Between Subsidy Duration and Cost

- Some immediate conclusions
  - When subsidies are too high, the cost increases without decreasing duration
  - When subsidies are low, both cost and duration increase
  - There is a range of intermediate subsidies for which subsidy cost and duration are in efficient tension with each other



A Closer Look at the Cost vs. Duration Trade-Off of Subsidies

- Intermediate range of subsidies for which reasonable outcomes are possible, *i.e.*, relatively small subsidy duration combined with reasonably low cost



Summary

- The adoption of new technologies with large externalities can be challenging
- Bundling and subsidies are two possible approaches to dealing with this challenge

- Bundling can be effective, but depends on the correlation in how users value the bundled technologies
  - Positive correlation attracts early adopters to reach critical mass
  - But too much positive correlation means many users who don’t value either technology
- Subsidies can overcome initial adoption hurdle, but identifying the right subsidy level can be challenging
  - Subsidies that are either too low or too high can result in significant over-costs and/or long subsidy durations
  - There is an intermediate range of subsidies that realizes a reasonable trade-off