Overcoming the Challenges of Network Technology Adoption

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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


The Adoption Conundrum of Network Technologies

- Useful above a certain adoption threshold, but how to get there?
The Adoption Conundrum of Network Technologies

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

- 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)…

- Sweden deploys DNSSEC in 2005
- IANA signs the root zone of the DNS in 2010
- Still barely a few % of sites in 2014…

From https://eggert.org/meter/dnssec (sample of ~7300 sites)
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
  \[ V_i(x_i(t)) = U_i + e_i x_i(t) - c_i, \]
  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 \( \iff V_i(x_i(t)) > 0 \), 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
  \[ V(x(t)) = U + e x(t) - c \]
  \- 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 “\( \text{When is } x^* \geq \max\{x_1^*, x_2^*\} \)”, 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 ($\rho$)
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 $1-u_i$ 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)

<table>
<thead>
<tr>
<th>Combination</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$\frac{c}{c - \varepsilon}$</th>
<th>$\frac{2 - c}{2 - \varepsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0)</td>
<td>$c_1 &gt; 1$</td>
<td>$c_2 &gt; 1$</td>
<td>SS True</td>
<td>WW False</td>
</tr>
<tr>
<td>(0, $\frac{1-c_2}{1-\varepsilon_2}$)</td>
<td>$c_1 &gt; 1$</td>
<td>$e_2 &lt; c_2 &lt; 1$</td>
<td>SL True</td>
<td>WW False</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>$c_1 &gt; 1$</td>
<td>$c_2 &lt; e_2 \wedge 1$</td>
<td>SL True</td>
<td>WL True</td>
</tr>
<tr>
<td>(1, $\frac{1-c_1}{1-\varepsilon_1}$, 0)</td>
<td>$e_1 &lt; c_1 &lt; 1$</td>
<td>$c_2 &gt; 1$</td>
<td>LS True</td>
<td>LW False</td>
</tr>
<tr>
<td>(1, 0)</td>
<td>$c_1 &lt; e_1 \wedge 1$</td>
<td>$c_2 &gt; 1$</td>
<td>LS False</td>
<td>LW False</td>
</tr>
<tr>
<td>($\frac{1-c_1}{1-\varepsilon_1}$, $\frac{1-c_2}{1-\varepsilon_2}$)</td>
<td>$e_1 &lt; c_1 &lt; 1$</td>
<td>$e_2 &lt; c_2 &lt; 1$</td>
<td>LL False</td>
<td>LW False</td>
</tr>
<tr>
<td>($\frac{1-c_1}{1-\varepsilon_1}$, 1)</td>
<td>$e_1 &lt; c_1 &lt; 1$</td>
<td>$c_2 &lt; e_2 \wedge 1$</td>
<td>LL False</td>
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<td>$c_1 &lt; e_1 \wedge 1$</td>
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<td>LL False</td>
<td>SS True</td>
</tr>
</tbody>
</table>
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 \(p \in [0,1]\)

<table>
<thead>
<tr>
<th>(U_1 \setminus U_2)</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>((1 - p)/2)</td>
<td>(p/2)</td>
</tr>
<tr>
<td>1</td>
<td>(p/2)</td>
<td>((1 - p)/2)</td>
</tr>
</tbody>
</table>

- 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 \(\rho\)
Equilibria Under Discrete Valuations

- Separate equilibria
  \[ l_i = \frac{(c_i - 1)}{e_i} \text{ and } r_i = \frac{c_i}{e_i} \]

- Three possible equilibria
  0, 1/2, and 1

- Bundle equilibria
  \[ l = \frac{(c - 2)}{e}, m = \frac{(c - 1)}{e}, \text{ and } r = \frac{c}{e} \]

- 3 possible equilibria:
  0, (1 + \rho)/4, (3 - \rho)/4, and 1
A Pictorial View of When (and Why) Bundling Can Help?
Both \textit{WW} and \textit{LL} Outcomes

<table>
<thead>
<tr>
<th>\textbf{SepEq}</th>
<th>\textbf{SepEq conditions } \Rightarrow</th>
<th>\textbf{BundleEq conditions } \Rightarrow</th>
<th>0</th>
<th>\frac{1+\rho}{4}</th>
<th>\frac{3-\rho}{4}</th>
<th>1</th>
</tr>
</thead>
</table>
| (0, 0)         | \begin{align*}  
c_1 > 1 \\
 c_2 > 1
\end{align*} | \begin{align*}  
\text{SS} \\
\text{True}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} | \begin{align*}  
\text{False}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} |
| (0, 1/2)       | \begin{align*}  
c_1 > 1 \\
 c_2 < 1 \\
 e_2 < 2c_2
\end{align*} | \begin{align*}  
\text{SL} \\
\text{True}
\end{align*} | \begin{align*}  
\text{WL}
\end{align*} | \begin{align*}  
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\text{WW}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} |
| (0, 1)         | \begin{align*}  
c_1 > 1 \\
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\end{align*} | \begin{align*}  
\text{SL} \\
\text{True}
\end{align*} | \begin{align*}  
\text{WL}
\end{align*} | \begin{align*}  
\text{WL}
\end{align*} | \begin{align*}  
\text{WS}
\end{align*} | \begin{align*}  
\text{WS}
\end{align*} |
| (1/2, 0)       | \begin{align*}  
c_1 < 1 \\
 e_1 < 2c_1 \\
 c_2 > 1
\end{align*} | \begin{align*}  
\text{LS} \\
\text{False}
\end{align*} | \begin{align*}  
\text{LW}
\end{align*} | \begin{align*}  
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\text{WW}
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\text{WW}
\end{align*} |
| (1, 0)         | \begin{align*}  
c_1 < 1 \\
 e_1 > 2c_1 \\
 c_2 > 1
\end{align*} | \begin{align*}  
\text{LS} \\
\text{False}
\end{align*} | \begin{align*}  
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\end{align*} | \begin{align*}  
\text{LW}
\end{align*} | \begin{align*}  
\text{SW}
\end{align*} | \begin{align*}  
\text{SW}
\end{align*} |
| (1/2, 1/2)     | \begin{align*}  
c_1 < 1 \\
 e_1 < 2c_1 \\
 c_2 < 1 \\
 e_2 < 2c_2
\end{align*} | \begin{align*}  
\text{LL} \\
\text{False}
\end{align*} | \begin{align*}  
\text{LL}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} | \begin{align*}  
\text{WW}
\end{align*} |
| (1/2, 1)       | \begin{align*}  
c_1 < 1 \\
 e_1 < 2c_1 \\
 c_2 < 1 \\
 e_2 < 2c_2
\end{align*} | \begin{align*}  
\text{LL} \\
\text{False}
\end{align*} | \begin{align*}  
\text{LL}
\end{align*} | \begin{align*}  
\text{WL}
\end{align*} | \begin{align*}  
\text{WL}
\end{align*} | \begin{align*}  
\text{WS}
\end{align*} |
| (1, 1/2)       | \begin{align*}  
c_1 < 1 \\
 e_1 > 2c_1 \\
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\text{LL}
\end{align*} | \begin{align*}  
\text{SW}
\end{align*} | \begin{align*}  
\text{SW}
\end{align*} |
| (1, 1)         | \begin{align*}  
c_1 < 1 \\
 e_1 > 2c_1 \\
 c_2 < 1 \\
 e_2 < 2c_1
\end{align*} | \begin{align*}  
\text{LL} \\
\text{False}
\end{align*} | \begin{align*}  
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\end{align*} | \begin{align*}  
\text{LL}
\end{align*} | \begin{align*}  
\text{LL}
\end{align*} | \begin{align*}  
\text{SS}
\end{align*} |

- **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 $\rho$ (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, **but not too much!**

\[c_1 = \frac{4}{3}, \quad c_2 = \frac{1}{3}, \quad e_1 = 1, \quad x_2^* = \frac{1}{2}, \quad x_1^* = 0\]

\[c_1 = \frac{3}{4}, \quad c_2 = \frac{1}{2}, \quad e_1 = 0, \quad x_2^* = \frac{1}{2}, \quad x_1^* = x_2^* = \frac{1}{2}\]

\[c_1 = \frac{5}{3}, \quad c_2 = \frac{1}{3}, \quad e_1 = \frac{7}{3}, \quad x_2^* = \frac{1}{2}, \quad x_1^* = 0\]

\[c_1 = \frac{3}{2}, \quad c_2 = \frac{3}{4}, \quad e_1 = \frac{3}{2}, \quad x_2^* = \frac{1}{2}, \quad x_1^* = x_2^* = \frac{1}{2}\]
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
  \[
  \dot{x}(t) = \gamma \left( P[V(x(t)] - x(t) \right), \gamma > 0, \text{ i.e., the rate of change in adoption is proportional to the difference between the fraction of users who would adopt given an adoption level of } x(t), \text{ and those who have adopted}
  \]

• 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

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

- The most interesting regime is when

$$u_M < c < u_m + e$$

In this scenario, $x^o(c)$ is an 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 $T_{FS}^o$, 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 $x^0(c)$ 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