Heterogeneity and the Dynamics of Technology Adoption

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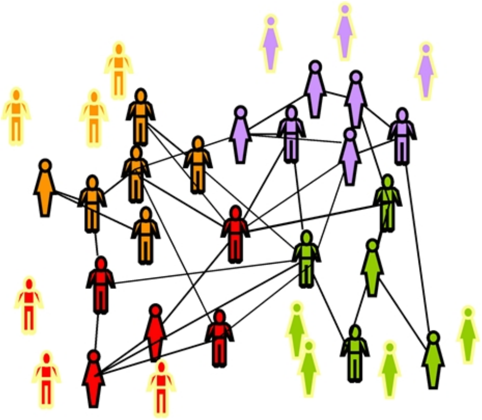
Network Technologies



Motivation and Research Question

- Technological progress is the heart of economic growth
  - Griliches (1957), Mansfield (1961) focused on how individual heterogeneity in adoption benefits affects diffusion dynamics: timing, rate, depth
  - Katz and Shapiro (1985), Farrell and Saloner (1985), Economides (1995) illustrate how network effects can lead to coordination failures
- Our aim: integrate these two literatures
- Research question: How does heterogeneity in adoption costs and use benefits affect diffusion of network technologies?
  - Is a firm policy of broad adoption better than one of targeted adoption?
- Big picture: estimating demand for network goods

Research Approach

- Data on videoconferencing technology adoption and use in a multinational investment bank from start to steady state
- Utility-based dynamic model of network evolution and use, with heterogeneity in adoption costs, network use benefits, and variety-seeking agents
- Propose a new estimator to recover the parameters governing sequence of calls made in a period
- Using recent two-step techniques for estimating dynamic games, recover the fixed costs of adoption
- Identification idea: ex-post usage proxies for value, adoption timing traces out distribution of fixed costs
- Evaluate two counterfactual adoption policies: uniform and targeted

Preview of Results

- Find substantial heterogeneity in adoption costs and usage patterns
- Most employees prefer to call other workers in their same region, function, and title
- Employees also value calling different types over sequence of calls
- Targeted policy is more effective in growing network and generating benefits than decentralized and uniform policies
- After accounting for fixed costs, uniform policy can actually be welfare-reducing

Videoconferencing Technology

- Network use of videoconferencing
- Stand-alone use of TV watching

Data: Potential Adopters

- HR Database of all 2,112 employees in large multinational investment bank

ID	FullTitle	Region	Function	Title
765	Chief Asian Macroeconomic Strategist	Asia	Research	Director
1256	VP New York Convertible Swaps Sales	US	Sales	VP

- Group each employee into one of 64 region-function-title types:
  - Region: Asia, British Isles, Europe, US
  - Function: Administration, Research, Sales, Trading
  - Title: Associates, VP, Director, Managing Director
- $x_i = \{\hat{e}^r, \hat{e}^f, \hat{e}^t\}$, where each $\hat{e}$ is a 1×4 unit vector. For example, a Vice President of Administration in Europe would be represented as $x_i = \{(0,0,1,0),(1,0,0,0),(0,1,0,0)\}$.

Data: Calls

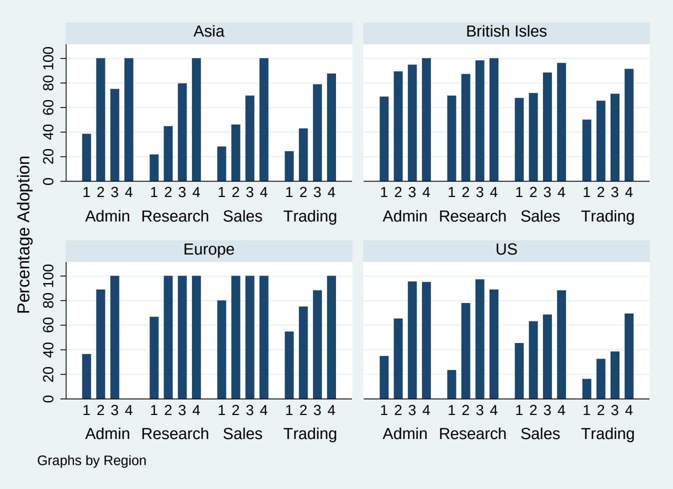
- Call Reporting Database, Jan 2001-Aug 2004, 463,806 calls

Callerid	Calleeid	CallType	StartTime	EndTime
765	1256	UsertoUser	2001-03-18 13:50:16	2001-03-18 14:10:21
1256	765	UsertoUser	2001-03-21 11:12:56	2001-03-21 11:15:25

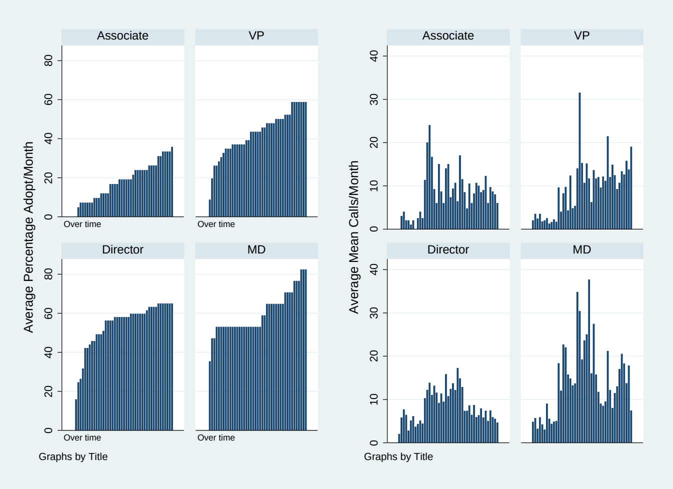
- Observation is the sequence of calls made within a month

Distribution of Employees

Distribution of Adoption Rates



Adoption Timing and Call Volume



Model Overview

- Construct a fully dynamic model of network evolution and use
- Decision period is one month
- The model is composed of two major components
  - Adoption Decision: In each period, agents outside the network decide whether to adopt and immediately use technology
  - Calling Decision: All agents within network can make as many calls to whomever they like in whatever order they wish
- Model matches three major moments of the data:
  - Variation in adoption rates across and within subtypes
  - Calling patterns vary across subtypes
  - Within a calling sequence, agents exhibit variety seeking

Calling Decision

- In each period, every employee makes a sequence of calls in order to maximize utility from using the network
- Define connection utility as:

$$U_{ijk} = \underbrace{\theta_1 + \theta_2' \Gamma}_{\delta_1} - \underbrace{\theta_3' \eta_j + \theta_4 (k-1)}_{\delta_2} + \epsilon_{ijk}. \qquad (1)$$

  - Define $\Gamma = (\gamma_{ij}^r, \gamma_{ij}^f, \gamma_{ij}^t)$, where:

$$\gamma_{ij} = (\hat{e}_{i1}\hat{e}_{j1}, \ldots, \hat{e}_{i4}\hat{e}_{j1}, \hat{e}_{i1}\hat{e}_{j2}, \ldots, \hat{e}_{i4}\hat{e}_{j2}, \hat{e}_{i1}\hat{e}_{j3}, \ldots, \hat{e}_{i4}\hat{e}_{j3}, \hat{e}_{i1}\hat{e}_{j4}, \ldots, \hat{e}_{i4}\hat{e}_{j4}). \qquad (2)$$

  - Γ function zeros out all the interaction terms which are not relevant for the connection between two given employees
  - Define η_j to be a 12×1 vector counting the number of times employee i has made calls to each of the characteristics
- The employee makes calls until the highest marginal call utility is negative

Adoption: Fixed Costs

- Denote the state space by s, where each element of this state space, s_{it}, reflects adoption decision of employee i at time t
- Each period, all agents outside the network may pay a fixed cost of adoption, F_i, and start using the network immediately
- Adoption is permanent
- The fixed costs represent variation in technical aptitude and the opportunity cost of learning how to use the technology, capture stand-alone benefits (e.g. TV)
- The fixed cost of adoption is time-invariant private information
- The distribution of fixed costs across subtypes is known by all agents

Adoption: Value Function

- Adoption decision is an optimal waiting problem: employee weighs the costs and benefits of adopting today against waiting to adopt in any future period
- In general, option value of waiting makes this problem complex
- Employee i adopts today iff:

$$EV_0(s_0) - F_i \geq \max\left\{0, \max_{t>0} \beta^t \left(EV_t(s_t) - F_i\right)\right\}.$$

- $EV_t(s)$ is the expected discounted present value of using the network after adopting t periods in the future
- Dynamics of problem arise here, since continuation value depends on beliefs of evolution of network and flow utilities of network usage

General Estimation Approach

- Continuation values are non-analytic, numerically impossible to compute: state space has 2^{2112} elements
- Follow two-step approach of Bajari, Benkard, and Levin (2006)
  1. Recover reduced-form policy functions describing the equilibrium strategies followed by each subtype as a function of s
     - Policy generating sequence of calls
     - Adoption policy
  2. Project policy functions onto underlying dynamic model to recover primitives
- Intuition: let agents solve the dynamic problem for us, policy functions reflect equilibrium strategies, and find primitives that make these strategies payoff maximizing
- Calling parameters do not depend on continuation value

Calling Policy Function

- Goal: Want to predict the calling sequence in the data
- Trick: Note that the probability of a calling sequence is equal to:

$$Pr(\Omega, K) = Pr(\Omega|K)Pr(K) \quad (3)$$

$$\ln Pr(\Omega, K) = \ln Pr(\Omega|K) + \ln Pr(K). \quad (4)$$

- Simulated sequence estimator breaks problem into two parts, uses maximum likelihood on first, MSM on second
- Monte Carlos show that this is more robust to small sample bias than joint estimation
- Identification: within-sequence variation identifies connection synergies, decay rates; length of sequences determines base utility, overall disutility of marginal calls

Adoption Policy Function

- Adoption policy for employees of subtype m as a function of the network at time t:

$$\begin{aligned} Proportion(adopt_m = 1; s_t, s_{t-1}, \lambda) = \\ \lambda_1' x_m + \lambda_2'(x_m \otimes \nu_t) + \\ \lambda_3'(x_m \otimes \nu_{t-1}) \end{aligned}$$

- Policy is function of ν_t is a 12×1 vector enumerating the counts of employee characteristics currently present in the installed base and operator $\otimes$ represents element-wise multiplication
- Inclusion of lagged terms controls for selection

Recovery of the Fixed Costs of Adoption

- Invert optimal waiting condition in terms of CDF of F_i:

$$Pr(adopt_i) = \Phi\left(E\left[U(\Omega_{it}) + \beta\left(V_i(s_{t+1}; s_{i,t+1} = 1) - V_i(s_{t+1}; s_{i,t+1} =\right.\right.\right.$$

- Can use policy functions and calling functions to simulate the network and assign payoffs to continuation values
- Policy function gives the probability of adoption
- Only unknown here are parameters of CDF—estimate using maximum likelihood
- For $t > 0$, correct for selection through conditional CDF

Results: Calling Parameters Region Interactions

Variable	Mean	StdDev
Asia to UK	-0.6600	0.0597
Asia to Europe	-1.0436	0.0942
Asia to USA	-1.9795	0.1309
UK to Asia	0.6670	0.0909
UK to UK	0.9514	0.0746
UK to Europe	1.5223	0.0699
UK to USA	0.9829	0.0733
Europe to Asia	0.5919	0.2800
Europe to UK	1.6874	0.2647
Europe to Europe	2.7498	0.2664
Europe to USA	0.1695	0.2769
USA to Asia	-0.6244	0.1519
USA to UK	0.9069	0.0979
USA to Europe	0.2601	0.1060
USA to USA	1.5474	0.0879

Results: Calling Parameters Function Interactions

Variable	Mean	StdDev
Administration to Research	-2.0443	0.0496
Administration to Sales	-1.4193	0.0472
Administration to Trading	-1.3955	0.0459
Research to Administration	2.6370	0.2032
Research to Research	2.4206	0.2023
Research to Sales	1.9498	0.2049
Research to Trading	1.7574	0.2013
Sales to Administration	0.2744	0.0841
Sales to Research	-0.6013	0.0707
Sales to Sales	0.3052	0.0819
Sales to Trading	-0.1223	0.0846
Trading to Administration	-0.2484	0.0678
Trading to Research	-1.5532	0.0749
Trading to Sales	-0.9859	0.0741
Trading to Trading	0.0832	0.0731

Results: Calling Parameters Title Interactions

Variable	Mean	StdDev
Associate to VP	0.0246	0.0436
Associate to Director	-0.3665	0.0516
Associate to Managing Director	-0.4850	0.0599
Vice President to Associate	-0.6165	0.0809
Vice President to VP	-0.4307	0.0801
Vice President to Director	-0.5650	0.0819
Vice President to Managing Director	-0.7572	0.0742
Director to Associate	-1.6287	0.1106
Director to VP	-1.1712	0.1006
Director to Director	-1.0022	0.0988
Director to Managing Director	-0.9161	0.1114
Managing Director to Associate	0.4116	0.1405
Managing Director to VP	0.6804	0.1395
Managing Director to Director	1.1702	0.1444
Managing Director to Managing Director	1.8718	0.1393

Calling Parameters: Decay Rates

Variable	Mean	StdDev
Intercept	-0.6862	0.0151
N	-0.6735	0.0010
decay Asia	-0.1685	0.0074
decay UK	-0.0674	0.0016
decay Europe	-0.0478	0.0015
decay USA	-0.0702	0.0017
decay Admin	-0.0569	0.0020
decay Research	-0.1210	0.0028
decay Sales	-0.0520	0.0021
decay Trading	-0.0446	0.0016
decay Associate	-0.1001	0.0024
decay Vice President	-0.0521	0.0011
decay Director	-0.0396	0.0012
decay Managing Director	-0.0546	0.0021

Fixed Adoption Costs in the US

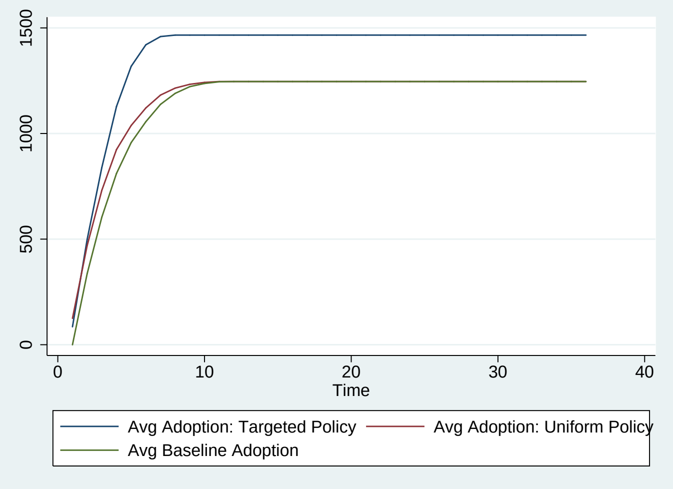
Subtype	Mean	S.E.	Variance	S.E.
Administration				
Associate	2.093	0.031	0.617	0.034
Vice President	1.622	0.034	1.040	0.026
Director	1.198	0.034	0.959	0.006
Managing Director	0.359	0.040	1.300	0.010
Research				
Associate	2.216	0.067	0.361	0.086
Vice President	1.420	0.081	0.993	0.079
Director	0.747	0.037	1.077	0.013
Managing Director	0.205	0.040	1.316	0.007
Sales				
Associate	1.904	0.030	0.779	0.030
Vice President	1.541	0.051	1.074	0.041
Director	1.179	0.041	0.961	0.007
Managing Director	0.719	0.030	1.087	0.010
Trading				
Associate	2.204	0.041	0.441	0.050
Vice President	2.092	0.031	0.581	0.033
Director	1.935	0.032	0.777	0.027
Managing Director	0.919	0.035	1.024	0.011

Policy Experiments

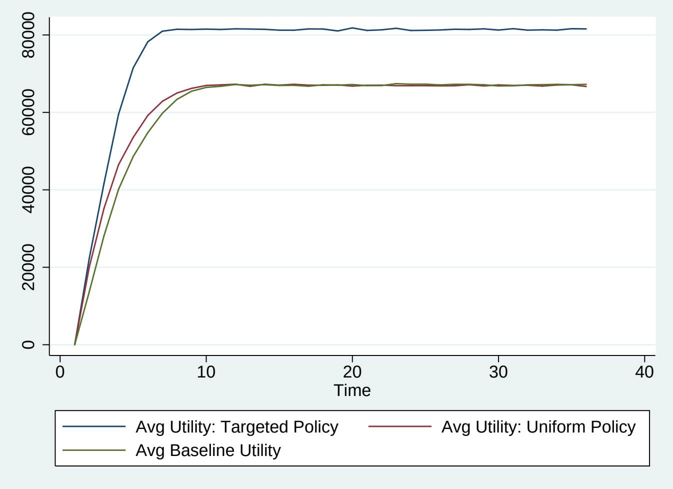
Evaluate two different technology diffusion strategies:

1. Start off in initial period by forcing Research Associate in US to join (Targeted Policy)
2. Start off in initial period by two people of each type to join (Uniform Policy)
3. Compare with baseline adoption strategy, which was decentralized adoption

Counterfactuals: Adoption Over Time



Counterfactuals: Average Utility



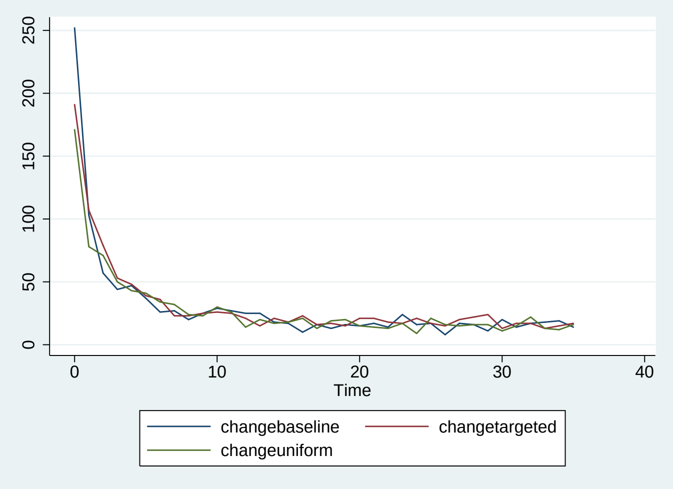
Counterfactuals: Summary Table

Variable	Baseline	Targeted	Uniform
Average Number of Calls	12.237	12.496	11.93
Maximum number of Adopters	1553	1690	1545
Present Value utility (mean)	403.1	426.6	418.9
Present Value utility (median type)	371.3	392.2	382.7
Present Value utility (25% type)	272.8	286.7	283.3
Present Value utility (75% type)	516.8	542.8	538.5
Discounted Value to Firm with $\beta = 0.9$			
Present Discounted Monthly Users	8904.8	10761.5	9542.9
Present Discounted Calls	107603.5	132763.1	114451.1
Discounted Value to Firm with $\beta = 0.99$			
Present Discounted Monthly Users	39371.1	44892.9	40218.8
Present Discounted Calls	484299.6	563224.0	494145.2

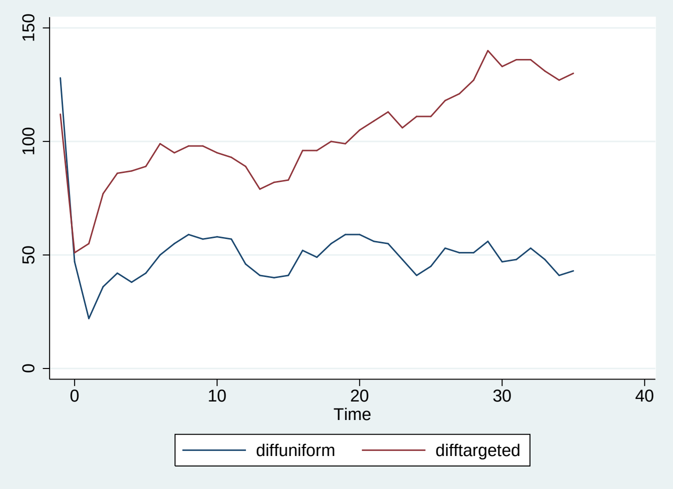
Conclusion

- Combine an older literature on heterogeneity in diffusion with the dynamics implied by network effects
- Examine how heterogeneity in adoption costs and usage across agents affects network evolution and use
- Our application is the diffusion and use of a videoconferencing technology in a large investment firm
- Develop a simulated sequence estimator to recover the primitives driving calling patterns
- Agents have heterogeneous adoption costs, calling preferences, and seek variety in calling within calling sequence
- The interaction of these three effects makes forming an optimal technology adoption policy a complex task
- Uniform adoption policies may be counterproductive, even when compared to the decentralized alternative

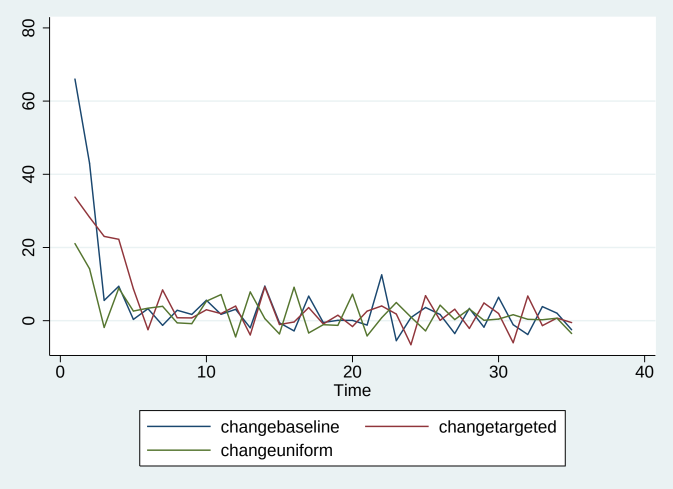
Policy Experiments: Change in Adopters



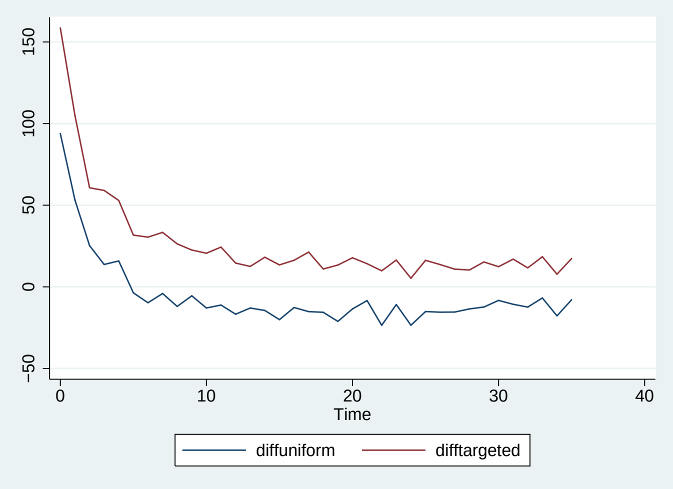
Policy Experiments: Difference in Adoption



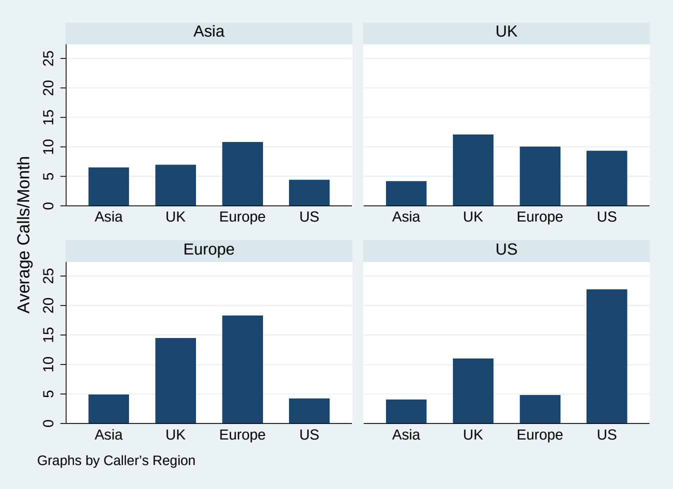
Policy Experiments: Change in Calls



Policy Experiments: Difference in Calls



Calls Across Regions



Calls Across Functions

Calls Across Titles