Cascades in Automation and Technology Adoption

Julian Klix

MRes Thesis Presentation

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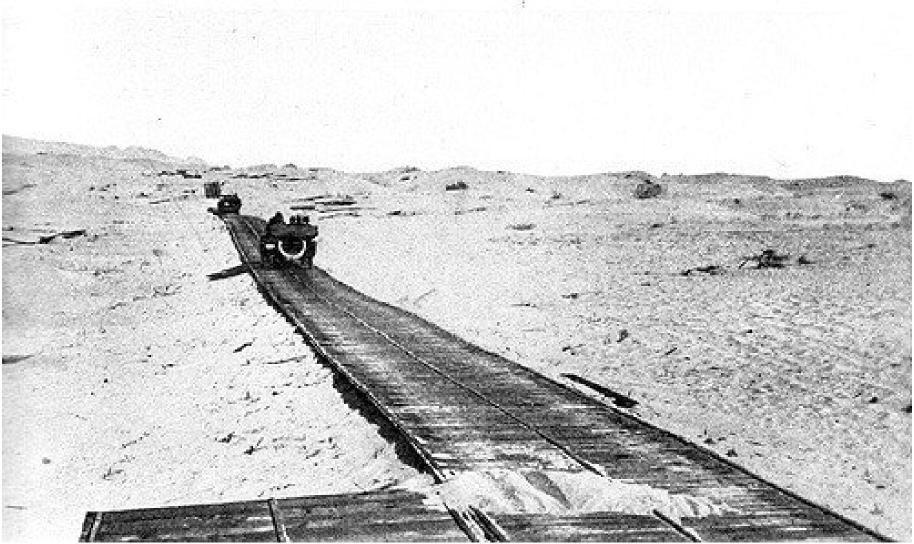
Introduction



Theoretical Literature

- Standard Herding: Banerjee (1992), **Bikhchandani et al. (1992)**
  - Uncertainty in values & private information
  - Sequential decision making (*exogenous queue*)
  - Observable actions

  ⇒ Occurrence of cascades: “Imitation dominates information”

- Endogeneizing queue order
  - Investment decision (Chamley & Gale, 1994)
  - Technology adoption (Kasahara, 2015)
- Interdependent values (Payoff externalities)
  - Pure network effect (Dasgupta, 2000)
  - Adoption reveals true state (Choi, 1997)

Experimental & Empiric Literature

- Herding behavior experimentally established
  - Standard Cascading (Anderson & Holt, 1997)
  - Limited reasoning depth (Kübler & Weizsäcker, 2004)
  - Herding with payoff externalities (Drehmann et al., 2006)

- Empirical evidence for technology adoption cascades
  - Agricultural sector (Rogers, 1974; Chatzimichael et al., 2014)
  - Plank roads (Bikhchandani et al, 1998)
  - Bank branches (Chaudhuri et al., 1997)
  - E-Commerce (Walden & Browne, 2003)

Baseline Model: Setup

- Values (= Profits) independent ⇒ isolated monopolies

- Unknown state $s \in \{H, L\}$ with $\mathbb{P}[s = 1] = p^s$: success of innovation
- Firm $i \in \{1, \ldots, n\}$: adopt ($a_i = 1$) or omit ($a_i = 0$)
- Private signal $\theta_i \in \{0, 1\}$ with $\mathbb{P}[\theta_i = \mathbf{1}_s(H)] = \lambda \geq 0.5$

- Profits $\pi(a_i, s)$ such that $\pi(1, H) > \pi(0, s) > \pi(1, L)$

- Firm's belief $\beta(\mathcal{I}_i) = \mathbb{P}[s = 1|\mathcal{I}_i]$ given available information $\mathcal{I}_i$

Baseline Model: Firm Behavior

- Firms maximize expected profit given available information $\mathcal{I}_i$
- Indifference between adopting and omitting at threshold $\bar{\beta}$:

$$\begin{aligned}\mathbb{E}_\beta[\pi(1,s)] &= \beta\pi(1,H) + (1-\beta)\pi(1,L) \\ &= \pi(1,L) + \beta\big(\pi(1,H) - \pi(1,L)\big) = \pi(0,s)\end{aligned}$$

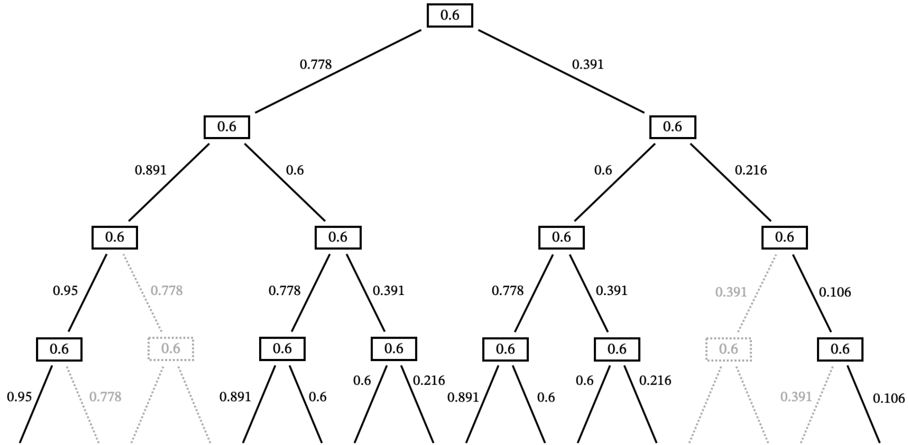
$$\bar{\beta} := \frac{\pi(0,s) - \pi(1,L)}{\pi(1,H) - \pi(1,L)} \in (0,1)$$

- Adopt ($a_i = 1$) whenever $\beta(\mathcal{I}_i) > \bar{\beta}$, omit ($a_1 = 0$) if $\beta(\mathcal{I}_i) < \bar{\beta}$
- Indifference $\beta(\mathcal{I}_i) = \bar{\beta}$: Follow private signal, $a_i = \theta_i$

Baseline Model: Innovation Cascades

- Use observable actions to make inference about previous signals
  $\Rightarrow$ Two components of information $\mathcal{I}_i = (\mathcal{I}_{i-1}, \theta_i)$
- $\mathcal{I}_j$ sufficiently described by $\Delta^a_j = \Sigma \mathbf{1}_{a_k}(1) - \Sigma \mathbf{1}_{a_k}(0) = 2\Sigma a_k - j$
- Three classes of behavior possible
  1. $\beta(\Delta^a_{i-1}, 1) > \bar{\beta} > \beta(\Delta^a_{i-1}, 0)$: Continue $a_i = \theta_i$
  2. $\beta(\Delta^a_{i-1}, \theta_i) > \bar{\beta}$: Adoption cascade with $a_i = 1$
  3. $\beta(\Delta^a_{i-1}, \theta_i) < \bar{\beta}$: Omission cascade with $a_i = 0$
- Cascades are absorbing ($\mathcal{I}_j = (\Delta^a_{i_c-1}, \theta_j)$ when emerged at $i_c < j$)

Baseline Model: Example



$$\Delta_i^a = 0, \theta_i = 1 : \beta(0,1) = \frac{p^s \lambda}{p^s \lambda + (1 - p^s)(1 - \lambda)} = \frac{0.6 \cdot 0.7}{0.6 \cdot 0.7 + 0.4 \cdot 0.3} = \frac{7}{9} \approx 0.778$$

Competitive Model: Setup

- Values (= Profits) interdependent ⇒ competing firms

- Unchanged general framework (decision structure, signal space)
- Profits $\pi_i(a_i, s)$ such that $\pi_i(1, H) > \pi(0, s) > \pi(1, L)$

  ⇒ Heterogeneous profit of successful adoption
- Payoff externalities $V_i(A_{-i}, s)$ with $A_{-i} = \Sigma_{j \neq i} a_j$
  - State-dependent: $V_i(\cdot, H) > V_i(\cdot, L)$
  - Increasing: $\partial V_i / \partial A_{-i} > 0$
- Total profits: $\Pi_i(a_i, A_{i-1}, s) = \pi_i(a_i, s) - \gamma V_i(A_{-i}, s)$

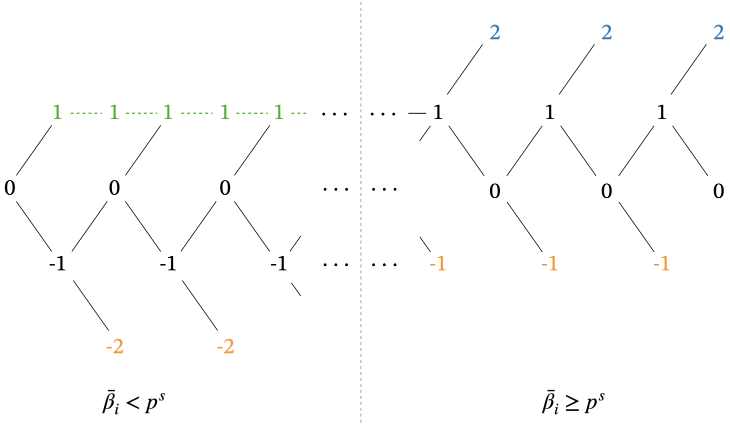
Diminishing Adoption Gains

- No competition $\implies$ firms still monopolists ($\gamma = 0$)
- Early adoption more profitable (e.g. hiring advantage)
  $\implies \pi_i(1, H) \geq \pi_j(1, H)$ for $i < j$
- Individual adoption threshold $\bar{\beta}_i$ similar to baseline

$$\bar{\beta}_i := \frac{\pi(0, s) - \pi(1, L)}{\pi_i(1, H) - \pi(1, L)}$$

  $\implies$ Increasing adoption threshold: $\bar{\beta}_i \leq \bar{\beta}_j$ for $i < j$
- Adoption attractiveness declines over time

Diminishing Adoption Gains



- Initial adoption cascades only temporary
- Initial omission cascades stable

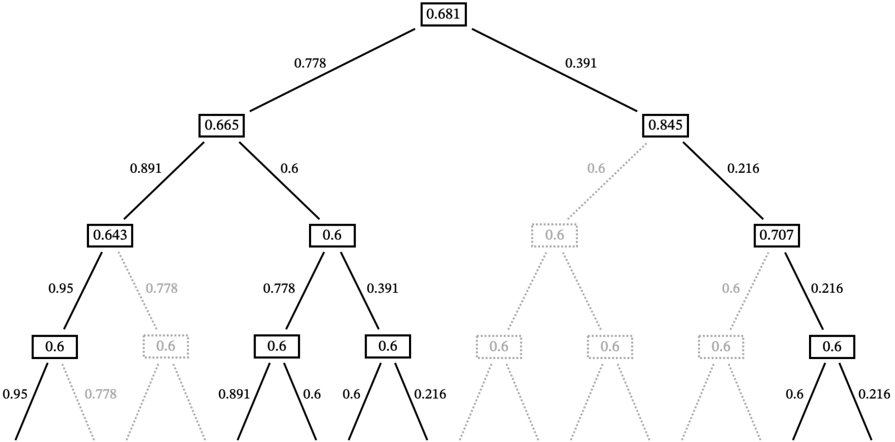
Market Interaction

- Firms compete in substitutes ($\gamma > 0$)
- Both **backward**- and **forward**-looking
  - Not solvable by forward induction $\Rightarrow$ Strategy convergence
- For any signal sequence, $\mathbb{E}_A[V_i|a_i = 1, s] \geq \mathbb{E}_A[V_i|a_i = 0, s]$
- Define the change in thresholds $\zeta_i(\gamma) := \bar{\beta}_i^M(\gamma) - \bar{\beta}_i$

Proposition 1

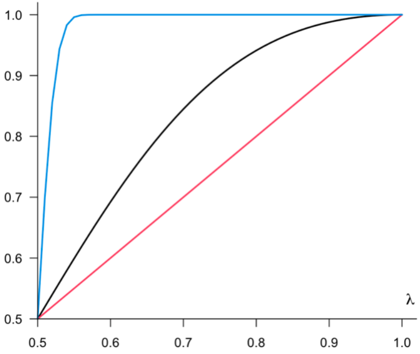
Under fixed strategies, competition between substitutes ($\gamma > 0$) raises the adoption threshold ($\zeta_i(\gamma) > 0$) and competition between complements ($\gamma < 0$) decreases it ($\zeta_i(\gamma) < 0$). Further, the threshold change ζ_i is increasing in competition intensity, i.e., $\partial\zeta_i/\partial\gamma > 0$.

Market Interaction

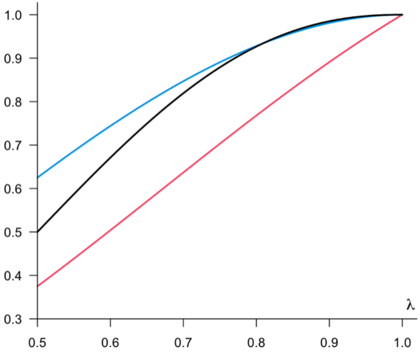


Results

- Probabilities of adoption cascades when $s = H$



Baseline (black), Public Signals (blue), Independent (red)



Baseline (black), Complements (blue), Substitutes (red)

Standard Intervention Methods [BHW]

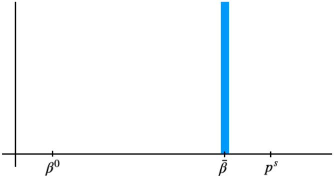
1. Policies targeting the correct action
   - Direct aggregate profit maximization
   - Recall $\pi(1,H) > \pi(0,s) > \pi(1,L) \implies a^c = \mathbf{1}_s(H)$
2. Policies targeting one specific action a^t
   - Ethic, social, environmental concerns
   - National security
   - Consumer welfare (e.g. market consolidation)

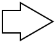
$\Rightarrow$ Standard BHW policy: public disclosure of θ_G with λ_G

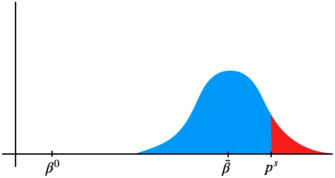
1. Disrupt any emerging cascade (increase aggregation)
2. Disrupt opposite cascades of $1 - a^t$

Incentive-based Intervention Methods

- Focus on decision incentives rather than belief formation
  $\Longrightarrow$ Methods to (indirectly) affect adoption thresholds $\bar{\beta}$
- Indiscriminate Monetary Intervention
  - Subsidize $a^t \Rightarrow$ adjusts $\bar{\beta}$ in the correct direction
  - Two-stage mechanism: Balanced by a universal tax
- Order-dependent Monetary Intervention
  - Heterogenize thresholds $\bar{\beta}_i$ (e.g. safeguard tariffs)

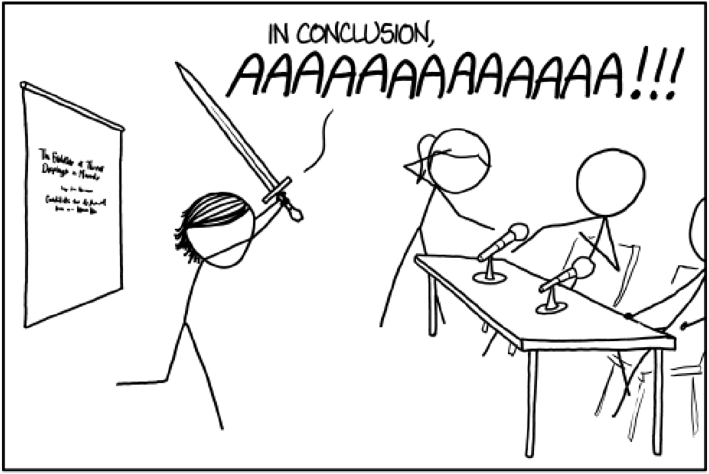






Conclusion

- One potential explanation for imitative adoption patterns
- General model of cascades with (asymmetric) payoff externalities
- Missing Micro-foundation of market behavior
- Avenues of further research
  - Two-layer model ($\Rightarrow$ micro-founded fundamentals π_i, V_i)
  - Imperfectly correlated adoption success s_i
  - Asymmetric observability (with *fashion-leaders*)



THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.

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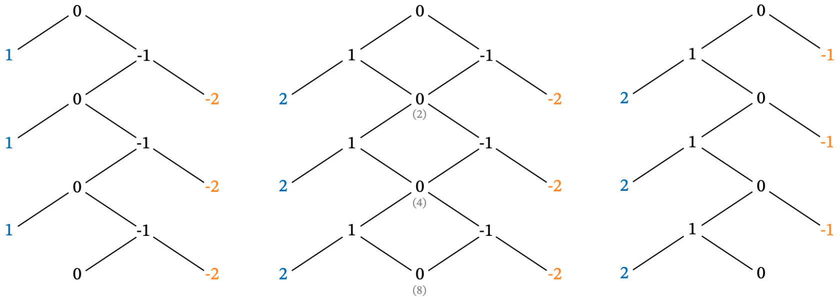
Automation as a Cascade

- Substantial patterns of deautomation (Camilo et al., 2020)
    - Indicative of uncertainty and learning processes
    - Matches instances of *disenchantment discontinuances* (Rogers, 1974)
- Exhibits signs of a technology trend
  "Companies new to the space can learn a great deal from early adopters who have invested billions in AI" (McKinsey Digital Report, Feb 2019)
- Data indicates sequential adoption decisions
- Relatively new technologies $\Longrightarrow$ predominantly private information
- Controversies about decision increases likelihood of observability

Baseline Model: Threshold Cases

- Starting points of cascades depend on $\bar{\beta}$ relative to p^s

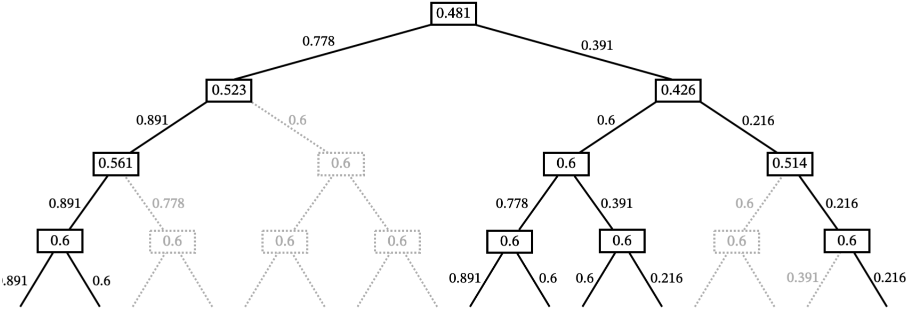


Case 3: $\bar{\beta} < p^s$ — $\Delta_{i-1}^{AC} = 1 \quad \Delta_{i-1}^{OC} = -2$

Case 1: $\bar{\beta} = p^s$ [BHW '92] — $\Delta_{i-1}^{AC} = 2 \quad \Delta_{i-1}^{OC} = -2$

Case 2: $\bar{\beta} > p^s$ — $\Delta_{i-1}^{AC} = 2 \quad \Delta_{i-1}^{OC} = -1$

Competition with Complements: Example



General Belief Formula

$$\beta(\Delta^a_{i-1}, \theta_i) = \frac{p^s \lambda^{\mathfrak{d}^+_i + \theta_i}(1-\lambda)^{(1-\theta_i)-\mathfrak{d}^-_i}}{p^s \lambda^{\mathfrak{d}^+_i + \theta_i}(1-\lambda)^{(1-\theta_i)-\mathfrak{d}^-_i} + (1-p^s)\lambda^{(1-\theta_i)-\mathfrak{d}^-_i}(1-\lambda)^{\mathfrak{d}^+_i + \theta_i}}$$

Case 1:

$$\mathfrak{d}^+_i := \text{median}(0, \Delta^a_{i-1}, 2) = \max(0, \min(\Delta^a_{k-1}, 2))$$

$$\mathfrak{d}^-_i := \text{median}(-2, \Delta^a_{i-1}, 0) = \min(0, \max(\Delta^a_{k-1}, -2))$$

Case 2:

$$\mathfrak{d}^+_i := \text{median}(0, \Delta^a_{i-1}, 2), \;\; \mathfrak{d}^-_i := \text{median}(-1, \Delta^a_{i-1}, 0)$$

Case 3:

$$\mathfrak{d}^+_i := \text{median}(0, \Delta^a_{i-1}, 1), \;\; \mathfrak{d}^-_i := \text{median}(-2, \Delta^a_{i-1}, 0)$$

Market Interaction Threshold

$$\bar{\beta}_i^M(\gamma) := \frac{\pi(0,s) - \pi(1,L) + \gamma \Delta V_i^L}{\pi_i(1,H) - \pi(1,L) + \gamma(\Delta V_i^L - \Delta V_i^H)}$$

where $\Delta V_i^s := \mathbb{E}_A[V_i|1,s] - \mathbb{E}_A[V_i|0,s]$

with $\mathbb{E}_A[V_i|a_i,s] := \mathbb{E}[V_i(A_{-i},s)|a_1,\ldots,a_i,s]$

Cascading Probabilities

Ex-Post Probabilities (Case 1)

$$p^{\text{cor}} = \frac{\lambda^2}{1 - 2\lambda(1-\lambda)}$$

$$p^{\text{inc}} = \frac{(1-\lambda)^2}{1 - 2\lambda(1-\lambda)}$$

$$p^{\text{noc}} = 0$$

Ex-Ante Probabilities (Case 1)

$$p^{\text{ad}} = \frac{p^s\lambda^2 + (1-p^s)(1-\lambda)^2}{1 - 2\lambda(1-\lambda)}$$

$$p^{\text{om}} = \frac{p^s(1-\lambda)^2 + (1-p^s)\lambda^2}{1 - 2\lambda(1-\lambda)}$$

$$p^{\text{no}} = 0$$

Cascade Probabilities by Cases

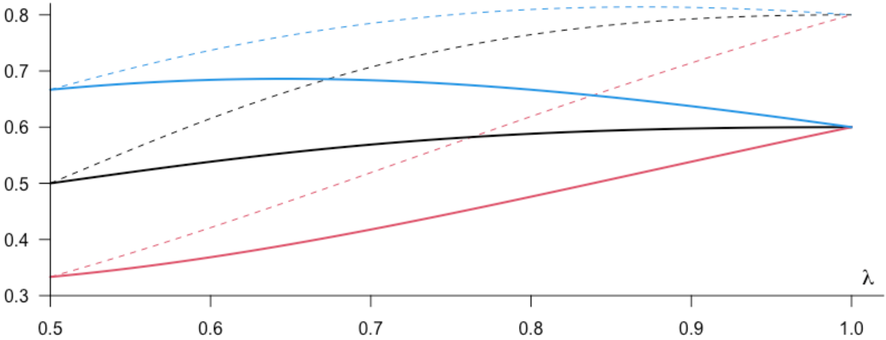


Figure: Probability of ending up in an adoption cascade in the limit ($n \to \infty$). The black line corresponds to the first case ($\bar{\beta} = p^s$) while the red (blue) line corresponds to the second (third) case with $\bar{\beta} > p^s$ ($\bar{\beta} < p^s$). Dashed lines represent the cascade probabilities with an increase in p^s.