The Technology Adoption Dilemma

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Abstract. *We develop a simple model of technology adoption based on evolutionary game theory that corresponds with intuition but also uncovers a non-ideal equilibrium that we call the technology adoption dilemma.*

Resumen. *Desarrollamos un modelo simple de adopción de tecnología basado en teoría de juegos evolutiva que corresponde con la intuición, pero que también revela un equilibrio no-ideal al que llamamos el dilema de adopción de tecnología.*

Keywords: technology adoption, evolutionary game theory, replicator dynamics.

Palabras Clave: adopción de tecnología, teoría de juegos evolutiva, dinámica del replicador.

Introduction

Technologies are not disruptive. Business models are. While Thomas Alva Edison advanced the ideas that made electrification possible, Samuel Insull launched electricity into the United States mainstream by exploiting economies of scale, cheap wiring, and innovative pricing structures that allowed small businesses and households to afford it. By the end of the 1920s, his user base rose from 5000 customers in Chicago to more than four million in 32 states (Chicagology, 2021; PBS, 2021).

Production of gasoline-powered automobiles began with Carl Benz in 1887 (Wikipedia, 2021). Still, it wasn't until 1908, when the Ford Company introduced the Model T—an affordable car built in a low-cost, standardized production line—that the automobile became affordable to the average citizen and became a household item (PBS, 2021).

In the early 1920s, the stick-thin flapper look was in vogue, and women wore the so-called "boyish form" to make them look flat-chested. Enid Bisset and Ida Rosenthal felt that women's dresses would fit better if they recognized the natural bust shape. An initial design that was later improved by William Rosenthal—Ida's husband—was built into a new garment named "the Maiden Form Brassiere" and incorporated in all their following dress designs. The overwhelming response from the market prompted them to establish a manufacturing operation (the Enid Manufacturing Company) specialized in producing the successful undergarment. They became the first intimate-apparel company to advertise in the media, driving up demand. To cope with the new market requirements and aided by Masha Hammer, the company created the first specialized production line in the women's apparel industry. By the end of the decade, more than a million Maiden Form brassieres were sold (Entrepreneur, 2008).

The launch of the iPhone in 2007 is a hallmark case of disruptive technology in the last century. While its initial success can be credited to product superiority, its continued success is tied to an innovative business model. Apple built an ecosystem that connected application developers with phone users, creating a new market for the internet and eventually challenging laptops as the device of choice for surfing the web (Christensen, Raynor, & McDonald, 2015). In an econometric study, (Korkeamäki & Takalo, 2012) conclude that patented technology constitutes only about 25% of the market value of the iPhone, capturing most

of its value out of its global supply chain, suggesting management and marketing abilities as significant determinants of its worth.

While technology-driven disruption has been an engine of progress since the beginning of history, the pace of development has increased so that we will witness more technological advancement in the next decade than we have seen in the last century (McKinsey, 2021; World Economic Forum, 2021). The consultancy identifies ten trends that will dominate the new environment based on which command more venture capital, file more patents, and have the most decisive competitive implications:

- Next level process automation and process virtualization (IoT, Robots, Cobots, RPA, Digital Twins, 3-D/4-D printing)
- Future of connectivity (5G and IoT connectivity)
- Distributed infrastructure (cloud and edge computing)
- Next-generation computing (Quantum computing, neuromorphic chips)
- Applied AI (computer vision, natural language processing, and speech technology)
- Future of programming (software 2.0)
- Trust architecture (zero-trust architecture, blockchain)
- Bio-revolution (Biomolecules, bio machines, biocomputing, bioaugmentation)
- Next-generation materials (nanomaterials, graphene, and 2-D materials)
- Future of clean technologies (nuclear fusion, smart distribution, battery storage, carbon-neutral energy generation)

The pandemic has accelerated the adoption of these technologies significantly (McKinsey, 2021), making it even more urgent to reflect on adoption. While the new developments promise substantial benefits in terms of efficiency, communication, safety, health, and well-being, they also threaten those not able or willing to ride the wave. Some authors go as far as speculating species-wide segregation (Harari, 2017; Kurzweil, 2005). While those views might be overly pessimistic, the effects of technology adoption on competitiveness are more vital than ever for individuals and enterprises alike.

This paper explores the dynamics of technology adoption under the lens of evolutionary game theory by developing a simple theoretical model based on the replicator dynamics.

Theoretical Context and Methodology

The *replicator dynamics* framework (Schuster & Sigmund, 1983; Taylor & Jonker, 1978; Zeeman, 1980; Hofbauer, Schuster, & Sigmund, 1979) has been applied successfully in many fields ranging from biology to language adoption to economics. See for example (Accinelli, García, Sánchez Carrera, & Zazueta, 2021; Zazueta, Accinelli, & Quintas, 2021). This section describes basic ideas for the asymmetric case, loosely following the presentation in (Schechter & Gintis, 2016). The interested reader is encouraged to follow the more detailed discussion presented by Schechter and Gintis in chapters 8, 10, and 11.

Consider a two-player asymmetric game G with a strategy set $S = \{s_1, s_2, \dots, s_n\}$ and two populations. Individuals from *population 1* play strategy s_i with probability p_i , where $p_i \geq 0$ and $\sum p_i = 1$, and individuals from population 2 play it with probability q_i , where $q_i \geq 0$ and $\sum q_i = 1$. The *population states* are denoted by $\sigma = \sum p_i s_i$ and $\tau = \sum q_i s_i$ respectively.

The expected payoff of an individual from *population 1* playing strategy s_i against a randomly chosen individual from *population 2* is given by:

$$\pi_1(s_i, \tau) = \sum_{j=1}^n \pi_1(s_i, s_j) q_j,$$

and the expected payoff of two randomly chosen individuals from populations with states σ and τ is given by:

$$\pi_1(\sigma, \tau) = \sum_{i=1}^n p_i \pi_1(s_i, \tau) = \sum_{i,j=1}^n p_i \pi_1(s_i, s_j) q_j.$$

Payoffs for individuals in *population 2* are defined similarly.

It is reasonable to assume that the change in a subpopulation size is proportional to its current size and that subpopulations with strategies with a higher payoff than average (*i.e.*, $\pi_1(s_i, \tau) - \pi_1(\sigma, \tau) > 0$) will tend to grow. In contrast, those with strategies with lower payoffs will decrease. Under these assumptions, we can write the replicator dynamics as follows:

$$\begin{aligned} \dot{p}_i &= p_i [\pi_1(s_i, \tau) - \pi_1(\sigma, \tau)], \\ \dot{q}_i &= q_i [\pi_2(\sigma, s_i) - \pi_2(\sigma, \tau)]. \end{aligned}$$

Where the dot over a variable denotes derivative with respect to time. Note that this formulation doesn't assume hyper rationality—an often-criticized feature of classic game theory—as agents act myopically simply comparing their payoffs with the average without explicitly solving for an equilibrium.

The Model

We define the two-player *technology adoption game* with a strategy set $\{\text{adopt}, \text{don't adopt}\}$ and two populations that play the strategies with probability $p, (1-p)$ and $q, (1-q)$ respectively. The payoff matrix is given by:

		q <i>adopt(y)</i>	$(1-q)$ <i>don't adopt(n)</i>
p <i>adopt(y)</i>		a, b	$c, 0$
$(1-p)$ <i>don't adopt(n)</i>		$0, d$	e, f

Table 1. Technology adoption game payoff matrix.

Where $a, b, c, d, e, f > 0$.

Payoffs for each strategy are defined as follows:

$$\begin{aligned}
\pi_1(y, \tau) &= qa + (1-q)c, \\
\pi_1(n, \tau) &= (1-q)e, \\
\pi_1(\sigma, \tau) &= p\pi_1(y, \tau) + (1-p)\pi_1(n, \tau), \\
\pi_2(\sigma, y) &= pb + (1-p)d, \\
\pi_2(\sigma, n) &= (1-p)f, \\
\pi_2(\sigma, \tau) &= q\pi_2(\sigma, y) + (1-q)\pi_2(\sigma, n).
\end{aligned}$$

And the replicator dynamics are given by the following system of ordinary differential equations (ODEs):

$$\begin{aligned}
\dot{p} &= p(1-p)[(a-c+e)q + c - e], \\
\dot{q} &= q(1-q)[(f-d+b)p + d - f].
\end{aligned}$$

Results

We use linearization to examine the system's equilibria. The associated Jacobian matrix is:

$$J = \begin{pmatrix} (2p-1)[(c-a-e)q + e - c] & (p^2 - p)(c - a - e) \\ (q^2 - q)(d - b - f) & (2q-1)[(d-b-f)p + d - f] \end{pmatrix},$$

and the stability analysis of the fixed points is summarized in the table below.

Fixed point	Evaluated Jacobian	Eigenvalues	Stability
(0,0)	$\begin{pmatrix} c-e & 0 \\ 0 & d-f \end{pmatrix}$	$(c-e, d-f)$	Stable when $e > c$ and $f > d$
(1,0)	$\begin{pmatrix} e-c & 0 \\ 0 & b \end{pmatrix}$	$(e-c, b)$	Unstable
(0,1)	$\begin{pmatrix} a & 0 \\ 0 & f-d \end{pmatrix}$	$(a, f-d)$	Unstable
(1,1)	$\begin{pmatrix} -a & 0 \\ 0 & -b \end{pmatrix}$	$(-a, -b)$	Stable
$(\frac{f-d}{f-d+b}, \frac{e-c}{e-c+a})$	$\begin{pmatrix} 0 & -\frac{b(a-c+e)(d-f)}{(b-d+f)^2} \\ -\frac{a(c-e)(b-d+f)}{(a-c+e)^2} & 0 \end{pmatrix}$	$\left(\pm \frac{\sqrt{a}\sqrt{b}\sqrt{c-e}\sqrt{d-f}}{\sqrt{a-c+e}\sqrt{b-d+f}} \right)$	Unstable. Saddle when absolute value of eigenvalues is greater than zero.

Table 2. Stability analysis of the system's equilibria.

Not surprisingly, adoption by both populations— (1,1)—is always a stable equilibrium under our payoff assumptions, and full adoption by one population with no adoption at all by the other— (1,0) and (0,1)—are unstable. The non-adoption case— (0,0)—is the most interesting, as its stability depends only on the relationship between the payoffs of the *don't adopt* strategies, leaving open the possibility of a stable

equilibrium despite a higher payoff for both populations if they were both to play the adopt strategy! We call this case the *technology adoption dilemma*.

Table 1 shows the phase portraits of the main four cases in our model. The left panel illustrates scenarios where adopting a technology has a higher payoff than not adopting for one population and the inverse for the other. The non-adoption equilibrium is a saddle and full adoption is stable. The upper-right corner panel represents the case where both parties' adoption is a clear strategy and no-adoption becomes a source, deflecting any perturbation to the full-adoption scenario. The lower-right panel features the technology adoption dilemma, where the full non-adoption strategy becomes a sink when the payoffs of non-adopting are larger than adopting for each population, although full adoption represents a higher payoff for both.

Furthermore, the basin of attraction of the full not-adoption equilibrium seems to be determined by the location of the mixed strategy equilibrium

$$\left(\frac{f-d}{f-d+b}, \frac{e-c}{e-c+a}\right),$$

Illustrated in the bottom-right panel of Table 3, which is a saddle. Players perturbed from this point will be attracted by either adoption or non-adoption. This is illustrated in Table 4; as the payoffs of adoption increase, the basin of attraction of the full-adoption equilibrium grows larger. However, despite being a significant improvement from non-adoption as depicted in the lower-right panel, the basin of attraction of the latter remains.

Conclusions

We built a simple evolutionary model to study the dynamics of technology adoption. Our model's dynamics agree with general intuition but also suggest a non-intuitive result that we call the technology adoption dilemma. This situation prevents companies or individuals from adopting a profitable technology because individual adoption is less profitable, missing the point that full adoption represents a better deal for both populations. This result helps explain the low adoption rate of profitable technologies in countries such as México. Still, unlike the prisoner's dilemma, full adoption is a stable equilibrium that the right policy framework can foster.

Table 3. Different system dynamics as a function of e , c , d , and f . The technology adoption dilemma appears when $e > c$ and $f > d$.

Table 4. The basin of attraction of the non-adoption equilibrium decreases with a and b but remains significant.

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During his professional life, Jorge has helped his clients achieve cumulative savings of hundreds of millions of dollars through efficiency improvements and Shared Services operating models. His experience as a consultant includes Fortune 500 companies such as Caterpillar, Nokia, Sony, Campbell's Soup, and Mars among others. He is currently a researcher at the Universidad Autónoma de San Luis Potosí and management consultant.

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