Technology Adoption with Strategic Complements on a Network

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30 August 2023

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Research Objective

We study a model of costly technology adoption with network benefits that depend on the number of partners on the network who also adopt

Key Results

- Model gives a threshold for adoption on the number of neighbours who also adopt
- Alternative explanation for incomplete technology adoption on a network: without standard network frictions
- Maximal set of adopters can be fully described using a graph theoretic concept: the k-core
- Apply network properties to healthcare digitisation
- Technology adoption can be fragile when network is shocked

Context

- Firms in a network where links capture relationships: customer/supplier relationships, collaborations etc.
- Firms adopt technology at some fixed cost: reduces costs of co-ordination
- Critically benefits increase in the number of partners who adopt the technology
- Expect model to be useful in scenarios where agents are well informed and co-ordinated, and the fixed costs are high - e.g. in high-tech industries

Literature

Related Literature

- **Technology Adoption:** Girliches (*1957*, Metrica), Bass (*1969*), Farrel & Saloner (*1985*, RAND)
- **Technology Diffusion on a Network:** Granovetter (*1979*), Katz & Shapiro (*1985, AER*), Bannerjee (*1992*, QJE), Brandiera & Rasul (*2006, EJ*), Beaman (*2021, AER*), Jackson & Storms (*2023*)
- **Network games:** Ballester, Calvó-Armengol, Zenou (*2006, Metrica*), Belhaj, Bramoullé, Deroïan (*2014, GEB*), Harkins (*2013*), Gagnon & Goyal (*2017, AER*)
- **Discrete Maths:** Bollobás (1984), Łuczak (1991), Pittel, Spencer, & Wormwald (1996), Dorogotsev (2006, 2008).

Model

Set-up

- n firms on a weighted and directed network g, represented with an $n \times n$ non-negative matrix G.
- Firms simultaneously make adoption decision: set $x_i \in \{0, 1\}$.
- Firms are risk-neutral profit maximisers:

$$\pi_i = f\left(x_i\ ,\ \sum_j G_{ij} x_j\right) - C \cdot x_i, \tag{1}$$

- $f(\cdot)$ continuous, increasing in first argument, and $C > 0$.
- **Assumption:** *strategic complementarities.* i.e. $f''_{12} > 0$

Threshold Game

Best replies

$BR_i(\mathbf{x}_{-i}) = 1$ if and only if $\sum_j G_{ij} x_j \geq k$, for all i, for all C, and for some $k \in \mathbb{R}$.

Nash Equilibria

- There are multiple equilibria: form a complete lattice under set-inclusion
- Focus on the maximal equilibrium: coalition-proof and Pareto dominant

Definitions

Induced Sub-Graphs

Induced Sub-Graphs

Let g and h be graphs. Then h is an *induced sub-graph* of g if:

- Every node in h is also a node in g; and
- For every pair of nodes u, v in h the link uv is in a link in h if and only if uv is in a link in g.

k-cores

Generalised k-core

Let g be graph and let $k \geq 0$. The generalised k-core of g is the maximal induced sub-graph such that every node has at least weighted out-degree k within the sub-graph.

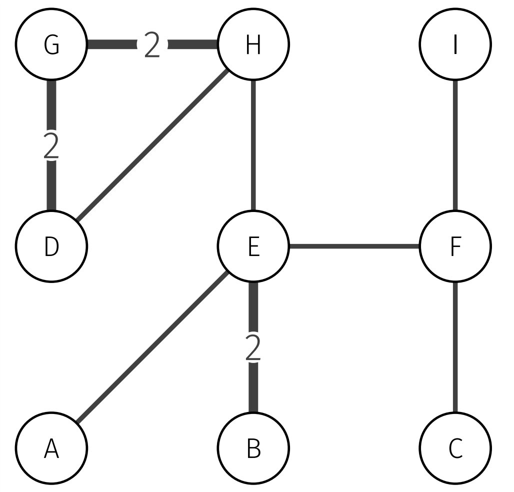
Describes well-connected agents in the graph who are neighbours of other well-connected agents

Finding the k-core

The k-core can be calculated using a simple algorithm which successively removes nodes which do not satisfy the out-degree threshold.

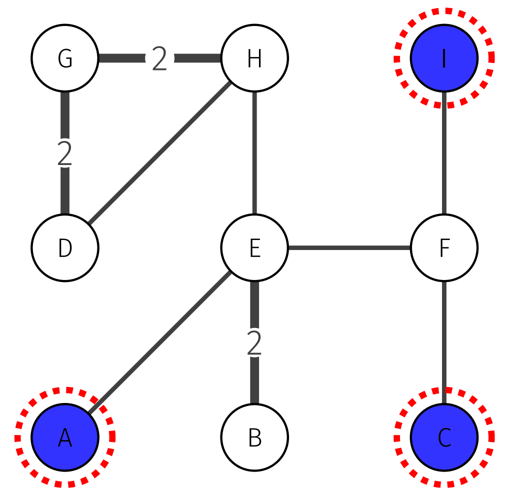
An example

$k = 1$



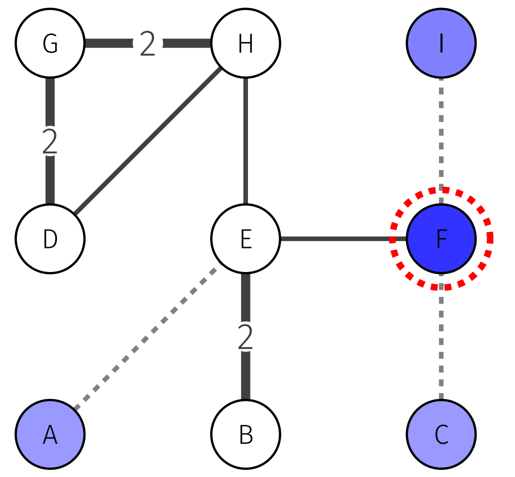
An example

$k = 2$



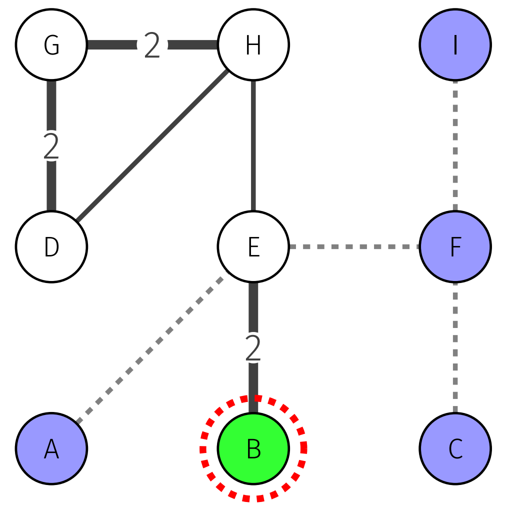
An example

$k = 2$



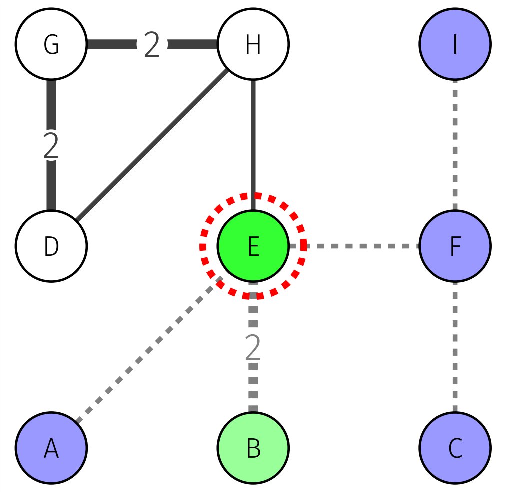
An example

$k = 3$



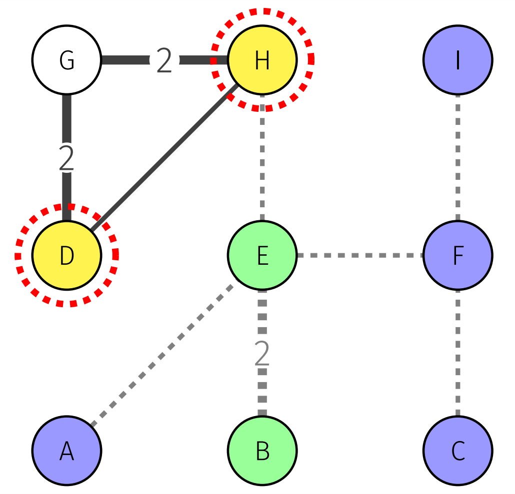
An example

$k = 3$



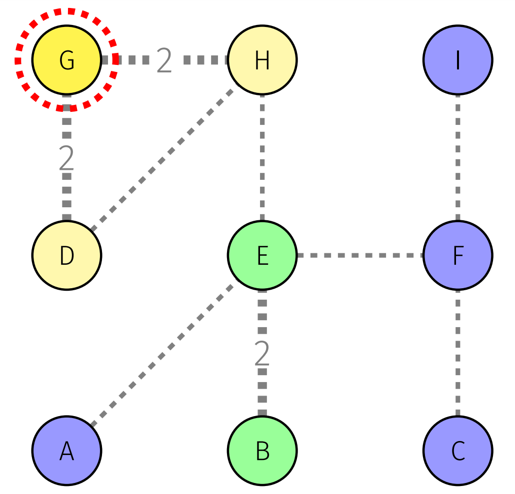
An example

$k = 4$



An example

$k = 4$



Results

Maximal Set of Adopters

Equilibrium actions

Let k be the threshold of the game. In the maximal Nash Equilibrium, $x_i^* = 1$ if and only if i is in the $k - core$.

Case Study

Case Study: Electronic Health Records

- Electronic Health Record (EHR): digital repository of patient data that is shareable across healthcare providers through Health Information Exchanges (HIEs)
- Empirical evidence that network effects play important role in cost-saving benefits of EHRs- strongest in dense networks with HIE participation (*Angst et al, 2010*; *Hilal et al, 2017*)
- EHR/HIE technology is expensive: only worth to adopting if you expect your neighbours to participate in HIE activities

Case Study: Electronic Health Records

- EHR/HIE technology created in 1980s but adoption was stubbornly low in early 2000s, despite policy efforts: in 2008 just under 10% of non-acute US hospitals had adopted
- Low adoption trend only broken by $19 billion HITECH Act in 2009

Case Study: Electronic Health Records

- Rural hospitals were particularly slow to adopt EHRs and have not reaped any cost saving benefits since adopting - primarily due to low HIE utilisation by partners (*Rhoades et al., 2022*) - Could networks explain this?
- Consider set of healthcare providers in the US to be a weighted network: providers linked if they share a patient
- *k*-core may be useful in understanding why rural hospitals were so hesitant to adopt
- Patient referral networks are less dense in rural areas: rural hospitals might not be in the *k*-core despite having many neighbours on the network

Urban patient referral networks are more dense than rural ones

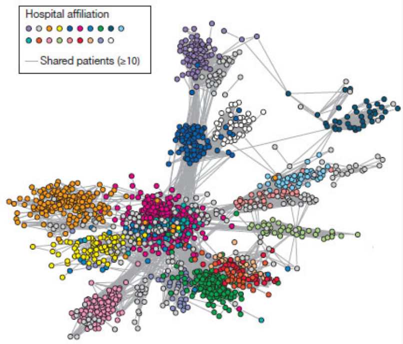


Figure 1: Sparse rural network: Albuquerque, NM (n=1391)

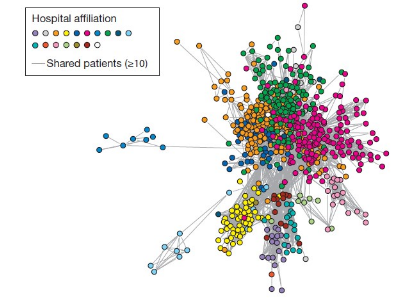


Figure 2: Dense urban network: Minneapolis/St Paul, MN (n=596)

Source: Landon et al, 2012

Thank you!

Unstable Networks

Technology Adoption with Uncertain Networks

- Firm needs make adoption decision a technology when at some unknown time a shock randomly removes a fraction of the firms from the network
- When the network have a non-empty k-core?
- Use random graphs to do this: classes of graphs where the number of neighbours each node is expected to have is governed by a pmf
- Results for un-weighted, un-directed graphs

Robustness of the k-core to random damage

Sudden disappearance of k-cores

Suppose a random network is drawn from the class of graphs with finite expected number of second neighbours. If nodes are deleted some nodes with probability pThen there exists a critical threshold $p(k)$ such that no firm in the original network is willing to take the action for all $p > p(k)$

The k-core undergoes a phase transition at $p_(k)$: it suddenly disappears

A small increase in shock probability can prevent technology adoption completely.