Diffusion

Innovation Boot Camp 2022

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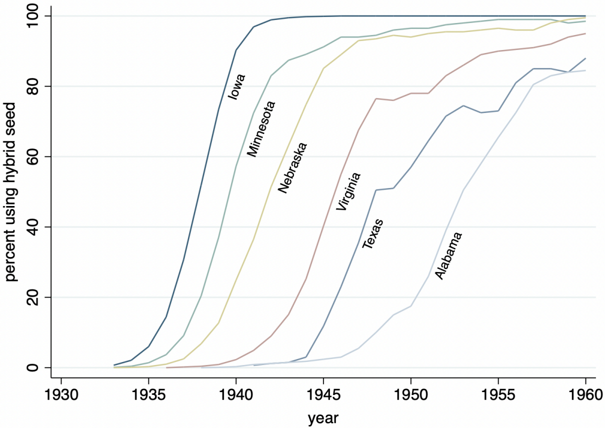
The simplest empirical problem

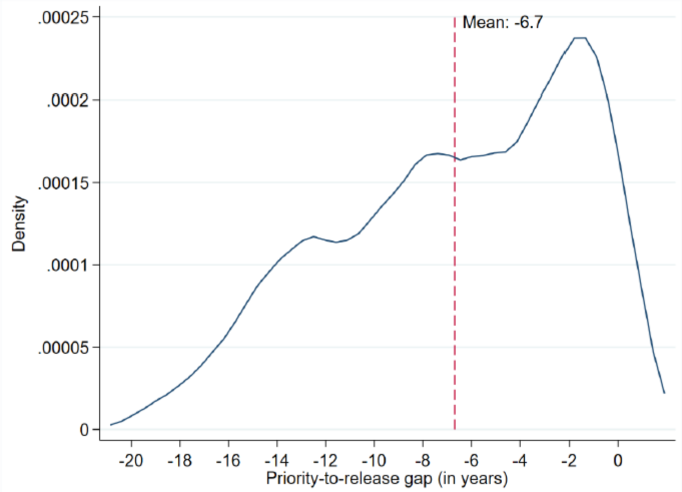


Note: The y-axis measures the percent of total corn acreage planted with hybrid seed by state, and also nationally. The graph shows the staggered implementation of hybrid corn across the corn belt in the US between 1930 and 1960. Source: Sutch, Libecap, and Steckel (2011), updating data from Griliches (1957)

The simplest empirical problem

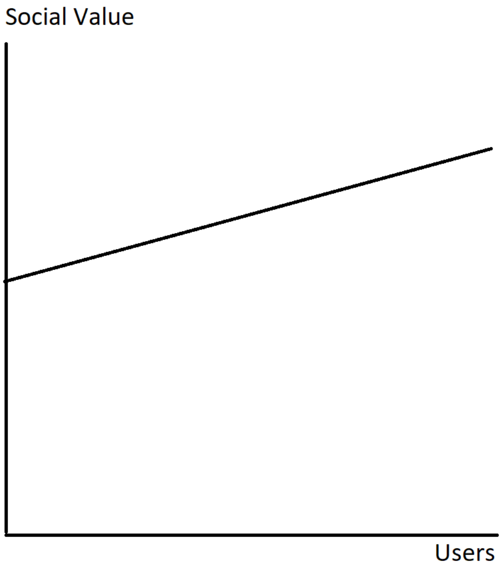
Line shafts in a late 1800s factory

The simplest empirical problem



From de Rassenfosse et al (WP) linked dataset of product introductions and patents

The even simpler theoretical problem



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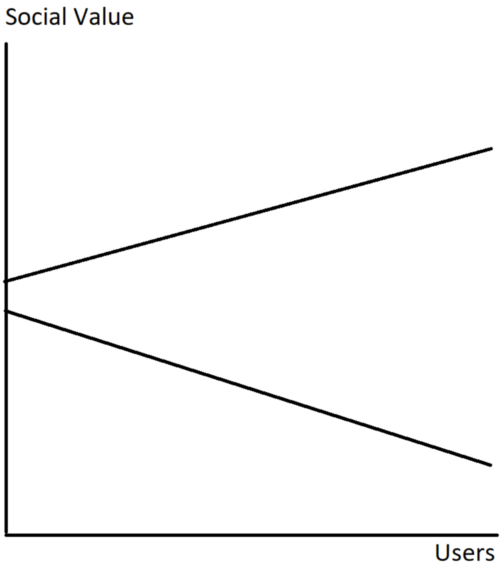

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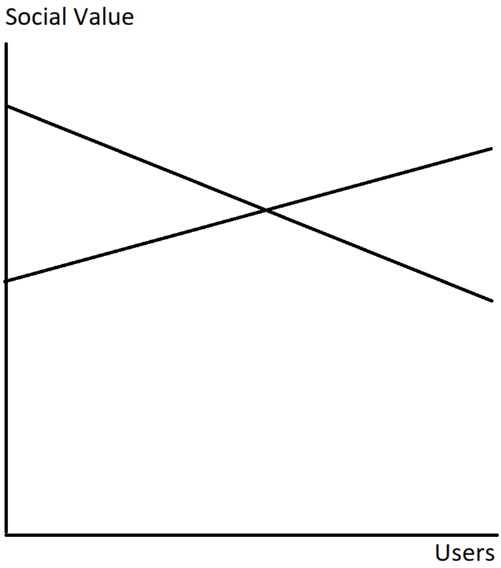

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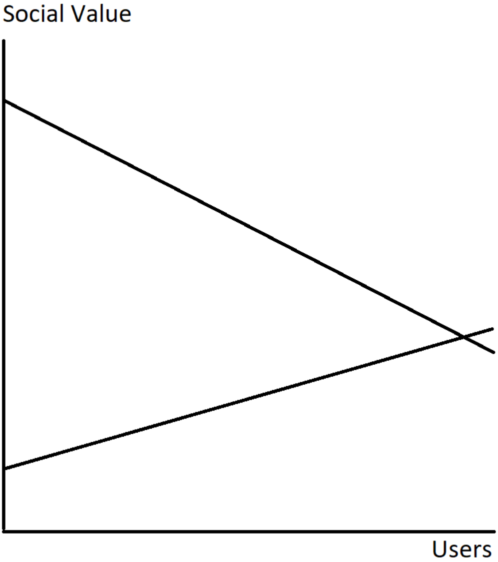


Defining diffusion

The social value of an innovation does not stop with an initial invention, but rather depends also on its diffusion

Diffusion: *the change over time in who produces and uses the invention, and where it is used and produced*

We will discuss two types of diffusion

- Technology diffusion: the adoption of a good by new users and in new places
- Knowledge diffusion: where ideas spread from one agent to another

Importance of diffusion

Social value of an innovation derives from the invention diffusing to new firms or plants, or to more varied final users

- Particularly relevant as global R&D is highly concentrated in a very small number of countries, and most firms do little R&D themselves
  - Diffusion of technology from those countries and firms is the main source of productivity improvement
- Critical inventions like electricity and the computer took decades to become commonplace in industries where both technologies are now fundamental [David 1990]

Historical ideas on diffusion

The fact that good ideas do not immediately spread has been studied by sociologists and anthropologists as far back as the late 19th century

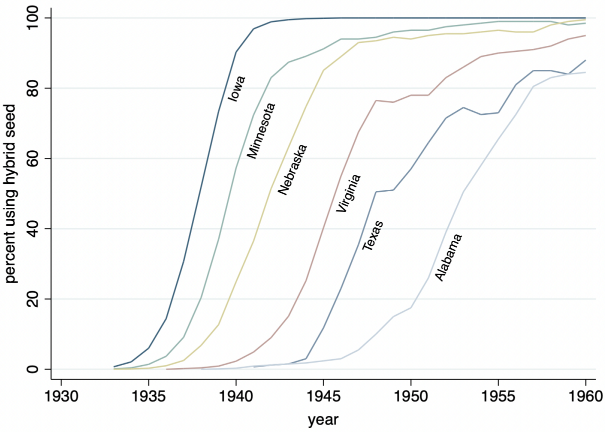
- Tarde (1890): Societal change depends on the diffusion of new inventions, which flow to new regions based on the amount of social contact and "logical laws"
- Chapin (1928) mapped the cumulative distribution function of a number of social innovations over time, finding an S-curve
  - Generally, innovations have slow initial adoption, then rapid uptake, then a slowdown as a market reaches saturation

Early empirical studies

Three canonical studies highlight mid-20th century work in this area

- Ryan and Gross (1943): Hybrid seen corn was known to many Iowa farmers in the early 1930s, but it was not commonly planted until the end of the decade
  - Authors argue adoption was driven by neighbors attesting to its benefit
- Coleman et al. (1957): The antibiotic "gammanym" diffused across Chicagoland doctors through social ties, especially early on, and particularly amongst professionally-oriented (rather than patient-oriented) doctors
- Griliches (1957): Hybrid corn is adopted slowly and diffuses following S-shaped adoption curves
  - Griliches divides the curve into three parts - "origin", "slope", and "ceiling" - and looks at how economic factors affect them

Percentage of total corn acreage planted with hybrid seed



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Consequences of diffusion

The time lag in adoption due to diffusion frictions is consequential on micro- and macro-grounds

Microeconomically:

- For example, Skinner and Staiger (2015) finds US heart attack patients have higher one-year survival rates at hospitals that adopt effective treatments (e.g. beta blockers, aspirin) quickly

Macroeconomically:

- Diffusion is critical to growth because cross-country differences in per capita output are too large to be explained by differences in factor inputs
- Eaton and Kortum (1999) gives a tractable structural model of innovation diffusion across regions
  - Domestic TFP increases when foreign inventions are used as inputs to final goods in the destination country, and when ideas in foreign inventions are used as the source of sequential inventions

Factors affecting diffusion

Many factors are thought to impact diffusion

Early literature:

- Information asymmetries mean that social networks smooth diffusion
- Adoption is costly in both a real sense and in terms of the option value of waiting to learn more

Recent Literature:

- Heterogeneity in adoption costs/benefits
- "Goldbricking" incentives among labor to prevent adoption

Information asymmetries

Asymmetric information, and hence the role for social contracts, as an explanation for slow diffusion goes back to sociological studies of ideas spread in the nineteenth century.

Firms introducing new products often make them similar to existing products in the same category to smooth this learning

- For example, Edison deliberately made the electric light as similar to existing gas technology as possible [Hargadon and Douglas 2001]

When the benefits of new technology are hard to observe, social learning can drive adoption.

Social learning

Empirically documenting evidence of social learning is a challenge given that social contacts likely share covariates

- Conley and Udry (2010) leverages the lengthy period between planting and the revelation of information about crop output to identify social learning as a driver of the diffusion of fertilizer-heavy pineapple crops in Ghana
- Adhvaryu (2014) studies a new malaria medicine in Tanzania which was rolled out quasi-randomly, finding that misdiagnosis of malaria and fever slows social learning and lowers future adoption
- Subsidies for tools that help social learning may be economically valuable

Information asymmetries can also be solved with non-social information, such as access to reference databases [Arrow et al. 2020]

Defining social learning

One must be careful to distinguish contagion, social influence, and social learning models of diffusion when comparing diffusion studies across disciplines

- Contagion model: implicitly assumes that diffusion requires social contact, often used in sociology and marketing
- Social influence model: based on wanting to conform to the choices of neighbors
- Social learning model: involves rational updating of beliefs about a technology on the basis of observing the choices and outcomes of friends

Costs of adoption

Many inventions must be explained in order to be used by others

Examples:

- Teece (1977): Costs of transferring knowledge about production made up 20% of the costs of moving production to a new plant in a multinational firm
- Glitz and Meyersson (2020): Active corporate espionage was required to keep East Germany from falling further behind the productivity frontier in the West
- Dudley (2017): Regions with a common language have historically produced disproportionate numbers of important inventions, particularly those which require cooperation among many inventors

Factors that reduce adoption or information costs, smoothing technology adoption across firms, consumers, or regions, are understudied

Option value

The decision to adopt a technology *today* must be weighed not just against nonadoption, but against adopting tomorrow

- When adoption incurs a fixed cost and information about the benefit of adoption is revealed over time, there's value in waiting
  - The decision to wait under social learning also imposes an externality to future adopters in one's social network
- Farzin et al. (1998): Theoretically, diffusion is slower than optimum for many sources of uncertainty about a new technology
- The option value of potentially free-riding on external innovation in the future distorts the rate of invention today [Benhabib et al. 2014]

To what extent do irreversible adoption decisions and the option value of waiting cause inefficient technological direction?

Option value and social learning in development

The combination of option value to adopting and social learning has been studied by development economists investigating why some highly productive inventions don't diffuse widely in developing regions

- Foster and Rosenzweig (1995): high-yield seeds in India are underused because farmers must experiment to learn of seeds' effectiveness; they can learn from others in their village, and they underexperiment due to this positive spillover
- Bandiera and Rasul (2006): Adoption of sunflower seeds amongst members of the same religion, or by friends and family, improves adoption probability

One potential lesson - the effect of ethnic or religious cleavages on information transfer, or the benefit of technology solving this information problem, are questions relevant to addressing global poverty

Not always inefficient to wait!

- The spinning jenny - a labor-saving invention in textiles which played a fundamental role in the Industrial Revolution in England - did not diffuse widely in France or India in the late 18th century
- Allen (2009) estimates that wages were not high enough in France or India for the spinning jenny to be cost effective until the relative price of the device compared to wages fell
- Prices of new inventions often fall due to scale economies or learning-by-doing [Arrow 1962]
- Diffusion lags may simply result from the fact that early adopters have higher value for the invention. Important to understand the externality!

Diffusion costs reduced by knowledge spillovers

Adoption costs for new innovations differ due to the local nature of knowledge spillovers

- Audretsch and Feldman (1996): Particularly in knowledge-intensive industries like computers or pharmaceuticals, innovation production is more geographically specialized than final goods production
- The same importance of local spillovers is evident in the geography of citations between patents and the concentrated location of high-growth new firms [Jaffe et al. 1993, Guzman and Stern 2020]
- Local technology diffuses more quickly due to lower adoption and search costs

These externalities have important policy implications (e.g. local tax incentizes could pull firms away from highly productive agglomerations) [Slattery 2020]

Standard-setting organizations

Standard-setting organizations (SSO) attempt to solve option value-related inefficiencies by creating standards to avoid wasteful innovation and marketing

- Simcoe (2012) develops a theoretical model of voluntary SSOs
- The internal organization and development of voluntary SSOs are important for efficiency
  - How to prevent "standard-essential" patent holders from demanding high license fees once the standard is established? [Lerner and Tirole 2015]
  - Implication of "forum-shopping" among different SSOs? [e.g., Lerner and Tirole 2006]

SSOs involve reciprocal patent licenses, so they might face efficiency concerns arising from patent pools [Hagiu and Yoffie 2013]

One important option value: complementary tech

Potential adopters have heterogeneous preferences or benefits of the technologies

- Fertilizer and hybrid seeds are not adopted by 40% of small-scale farmers in Kenya, because they lack the complementary technologies [Duflo et al. 2008, Bresnahan and Trajtenberg 1995]
- Gross (2018) finds that fixed-tread tractors did not spread to Midwestern farms until complemented by general-purpose tractors and cotton and corn farming technologies
- The role of complementary technology is particularly important when multiple agents must adopt simultaneously for a technology to be valuable
  - e.g. Basker and Simcoe (2021) finds manufacturers are more likely to adopt UPC codes when other manufacturers with the same retail partner have adopted them

Goldbricking

Diffusion may be limited because some agents benefit from preventing use of new technology

Goldbricking: Concealing the effectiveness of new technology, particularly labor-saving technology

- Lazonick (1979): Workers during the Industrial Revolution resisted the adoption of the self-acting mule, which was thought to reduce labor demand
- Atkin et al. (2017): Soccer ball producers in Pakistan do not adopt a highly efficient new method of preparing soccer balls because piece rate workers are not compensated for avoiding waste in production, but do lose wages when production slows as they learn the method
- When organizational practices are sticky, useful technologies may not diffuse rapidly [e.g. Gibbons and Henderson 2011]

Diffusion in health econ

- Agha and Molitor (2018): When cancer treatment clinical trials are led by a local scientist, patients in the region are 36% more likely to be given the drug in the two years after FDA approval
- Allen et al. (2019): Doctors learn over time as a function of geographic and medical school cohort similarity with doctors who learn about more effective treatments early
  - To diffuse accurate information, strengthening information flow over time in highly-connected parts of the network is more effective than targeting the initial beliefs of doctors
- At the country level, Kyle (2006) shows many drugs are introduced to some countries with substantial delay, or never launched at all, depending on whether inventing firms have experience in that or geographically/culturally similar countries

Diffusion in trade

In standard trade models, the gains from free trade are often thought to be counterintuitively low

Models that capture dynamic gains from trade (e.g. the effects of openness on firm productivity distribution) could resolve this concern

- Buera and Oberfield (2020) creates a model of diffusion where the crucial parameter is how important global ideas are to local productivity
    - Benefits of trade to growth are highest when this parameter is in an intermediate range: foreign ideas are important to productivity, but you can't learn everything that is useful just by importing a small variety of foreign products

Thus, the nature of frictions to diffusion is critical for welfare analysis of trade policy

Diffusion policies: Technology transfer requirements

Technology transfer requirements can help speed up diffusion

- Policies that increase technology transfer:
  - IP rules that incentivize transfers
  - Direct technology transfer requirements for producers
  - Subsidies and government programs, like agricultural extension services and deliberate transfer of productivity advice
- Reciprocity in treatment of foreigners in IP protection improves welfare by solving the free-riding problem of low innovation countries [Scotchmer 2004]
- Forced technology transfer also acts as a tax on initial innovators by shrinking the gap in productivity between innovators and beneficiaries
- Analysis of a Marshall Plan program in Italy found the transfer of management knowledge led to increased productivity and a higher probability of exporting even fifteen years after the program ended. [Giorcelli 2019]

Diffusion policies: Taxing foreign technology

Some countries tax foreign technology to promote domestic innovation and ensure that innovation is more “appropriate” for the domestic labor force

- de Souza (2020) studies effects of a 2001 law taxing foreign technology and subsidizing domestic innovation
- Firms that previously used technology from abroad to increase patenting, hire lower skilled workers, and decrease production

Broadly, the global level of technology is sufficiently high quality that skill mismatch alone does not mitigate against its use

Diffusion policies: Absorptive capacity

Absorptive capacity: Across and within firms, the ability to absorb invention from the outside depends on what the recipient knows

- Bilir and Morales (2020): 20% of the productivity benefits of innovation in the US by the median multinational firm accrues to foreign affiliates
  - Additionally, there is strong complementarity between those affiliates' R&D and this productivity gain
- Coe et al. (2009) finds that foreign R&D stocks benefit domestic TFP especially when the recipient nation is highly educated and has strong IP protection

The need for absorptive capacity may partially counteract the harms to R&D incentives caused by technology transfer requirements

Diffusion policies: Competition and diffusion

If diffusion is slow, productivity differences between firms can remain even in the absence of anti-competitive behavior

- Syverson (2004): 90th percentile firm in a given industry is almost twice as productive as the 10th percentile firm
- If technology diffusion requires active effort, policies which increase competition may change the incentive of incumbents to adopt frontier technology, or force low-productivity firms out of business if they don't adopt
  - Schmitz (2005): Competition with Brazilian mines forced American and Canadian iron ore mines to adopt organizational practices and labor contracts, doubling productivity
  - Bloom et al. (2016): Lower tariffs for Chinese producers forced European manufacturers to either adopt productivity-enhancing technology or exit the industry

Data limitations

- Dating back to Ryan and Gross (1943), most diffusion studies rely on hand-collected data about specific technologies
- Government and private sector datasets tend to have very limited data on diffusion of particular technologies, and tracing the source of diffusion is even harder
- Five classes of nonproprietary data which have proved useful:
  - CHAT
  - Scanner data
  - Census data
  - Patent data
  - New corpuses extracted using ML?

CHAT

For data on technology adoption over time and space, including the intensive margin of adoption in each location, the Cross-Country Historical Adoption of Technology (CHAT) dataset from Comin and Hobijn (2010) is the most extensive

- The dataset traces the intensity of adoption of over 100 technologies in 161 countries since 1800
- Importance of *intensity* data: the airplane was available in both China and US in 1960, but the number of flights was orders of magnitude higher in the US
- Comin and Mestieri (2018) argues that the intensive margin of diffusion, rather than the extensive margin, explains why incomes diverged between countries even as technology "arrived everywhere"

Scanner data

Scanner datasets contain panel information on precisely which products are available for sale when and where

- Some datasets are limited to specific industries (e.g. IRI Academic Dataset on foodstuffs)
- The standard cross-industry reference is the Nielsen Retail Scanner Dataset
  - Weekly data for millions of consumer-oriented UPCs from tens of thousands of stores since 2006
- Linking the diffusion data from Nielsen UPCs to other covariates in patent or hand-collected data has tremendous potential

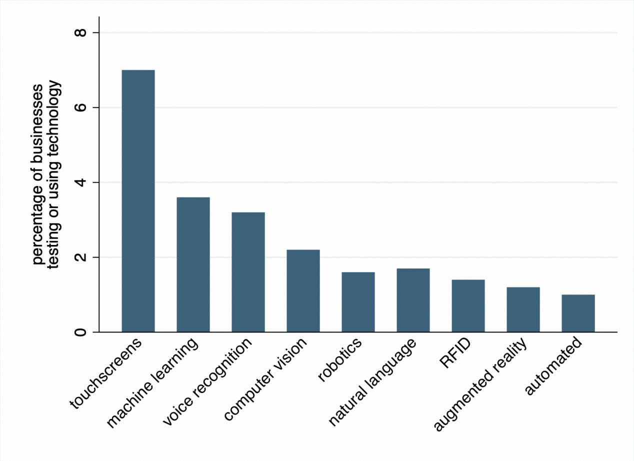
Census data

Standard population surveys in many countries have long tracked certain classes of consumer goods

Two surveys appear particularly promising for studying diffusion to firms:

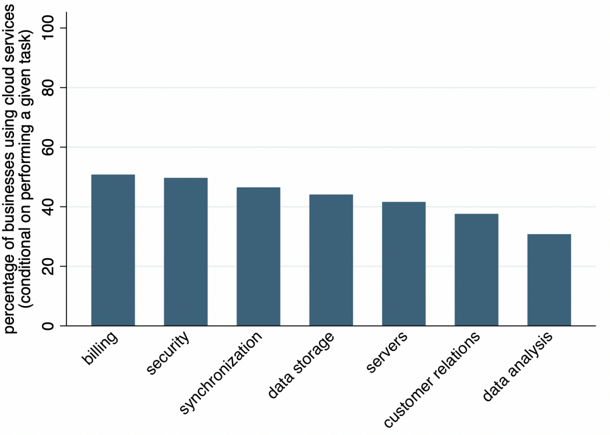
- US Census Annual Business Survey
  - First wave in 2018, it surveys 850,000 nationally representative businesses about their adoption of technologies
- World Management Survey
  - Deriving from Bloom and Van Reenen (2007), this survey asks managers in a growing number of countries about their adoption of process technologies

Adoption or trial of advanced technologies



Note: Data comes from the 2018 Annual Business Survey. The data are weighted to match all US firms on the basis of responses from over 570,000 businesses. Source: McElheran et al. (2020)

Adoption of cloud services



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Patent data

As with other questions in innovation, the "paper trail of knowledge" in patents has been a useful dataset for studying diffusion

- Jaffe et al. (1993) canonically shows that patents are 2-6x as likely to be cited by a future inventor in the same metropolitan area
  - Localization effect suggests that the ideas in a patent diffuse over space only with time
- Thompson and Fox-Kean (2005) reaches a similar result after comparing inventor patent citations and examiner-added citations
- Arora et al. (2018) cautions that "citation reversals" could result in imprecise data, but the citation reversals have nearly the same geographic decay as non-reversal citations

Text-based approaches

Researchers could look at the text of patents with machine learning to measure diffusion

- Myers and Lanahan (2021) investigates spillovers from SBIR grants targeted at particular technical problems
- The authors look at the cosine similarity between text in SBIR call for proposals and the full corpus of US patents in order to infer which technology classes the grant was targeting
- Findings:
  - Up to four patents overall are generated for each patent induced by the grant recipient
  - The citation network misses up to half of these spillovers
  - Spillovers are more likely to be geographically proximate

Text-based approaches plus patents

- Combining patent data with information about invention and external data on adoption by end users or non-patenting intermediate users is a promising future path
- The text of patents themselves often contains information written by inventors about the precursors of their invention, as leveraged in Bryan et al. (2020) and Marx and Fuegi (2020)

Non-patent datasets

- The arrival and expansion of new technology is clearly evident in non-patent data, and helps capture broader "technology spread"
- E.g., at what rate does air-based cropdusting arrive? Local newspapers highly likely to report on use of a new technology of this type. Melissa Dell and coauthors have an ongoing project to digitize all late 19th and early 20th century US newspapers in a high-quality OCR format. Topic modeling can identify air-based pest control without need for individual keyword search.
- Alternative large text- or image-based sources that could be searched?

Need for further research

- Despite the enormous social returns of specific inventions, once adopted there are very few credible estimates of the social return to policies which speed diffusion in the aggregate
- We need more research to understand where equilibrium investment in marketing and diffusing new products is inefficient, and which public policies can ameliorate these inefficiencies. Even the theoretical externalities are not totally clear.

Summing up

- The social value of an invention derives from the innovation diffusing to new firms and regions
- Diffusion is frequently impacted by information asymmetries and high costs of adoption
- Diffusion is often limited to local spillovers, with real impacts on trade, agricultural production, medicine, and other areas
- Social learning, standard-setting organizations, technology transfer requirements, and competition are among the potential tools to encourage diffusion of frontier technology
- More research is needed to shape policy that optimizes the social value of innovation via diffusion.