Digital Infrastructure: A Guide to the Empirical Economics Literature

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For the NBER Digitization Tutorial

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Thank you

- Thanks to Avi for giving me opportunity (and excuse) to put this together.
- Will present material quickly, & stress broad themes. You can read detail on your own.
- Will pause for short Q&A b/w sections. Happy to have extended conversations offline.

Goals today.

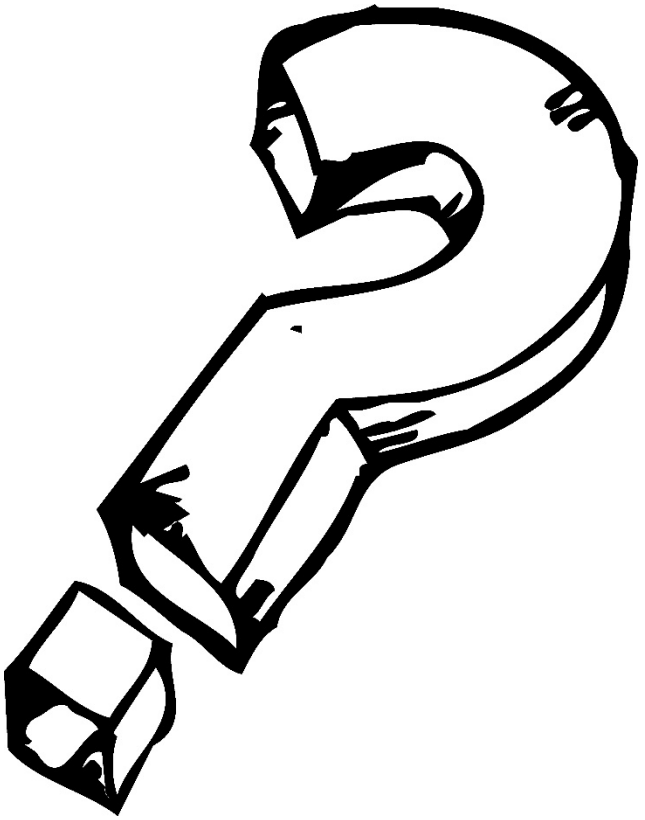
- What this talk does: Identify challenges and opportunities for economic research in digital infrastructure.
  - What are the most important (un)answered questions?
  - What are common errors and how can they be avoided?
- What talk does not do: Write your research proposal for you.
  - Will not underestimate your ability to take a creative approach to research.

The schedule

- Motivation
- Broadband
- Digital infrastructure more broadly
- Global deployment
- Pretentious & avuncular advice

Brief pause for Q&A

- Any questions?



What's next.

- **Motivation**
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  - **Why study this?**
  - **Why digital is similar but different from other infrastructure.**

Research on digital infrastructure faces an uphill battle

- Biggest academic challenge: get an audience.
  - <sarcasm alert> A strategy for losing readership: Put "infrastructure" in the title & work in areas that lack a policy consensus. <end>
- Yet, nonetheless, researchers write about digital infrastructure & policy issues. Why?
  - Puzzles are intellectually engaging.
  - Policy issues merit attention.
  - Uses combination of statistics & stories.
  - Of interest to academic/policy/industry audiences.

But…What is digital infrastructure? It depends on the context.

- **Narrowly construed**
- *Digital infrastructure* encompasses root servers, broadband lines, switches and routers, content delivery networks, data centers, cloud storage, cellular towers, and other physical assets.

- **Broadly construed**
- *Digital infrastructure* includes complementary skilled labor for operating infrastructure that appears in same locations as digital hardware.
- Includes both *provider* & *users* in a networked service, and both *public* & *private* providers of services.

Why study digital infrastructure? Associated w/creating value.

- In 2017 payments for access in wireline forms contributed over $88.7 billion to US GDP, growing more than 30% from 2012 (in nominal terms).
- Payments for access in wireless forms amounted to over $96.0 billion in 2017, growing more than 57% from 2012.
- Astoundingly fast diffusion of smart phones in one decade. More than ¾ of US pop. On top of ¾ of households with wireline broadband.
- Online advertising contributed $105.9 billion to GDP in 2017 among Internet Publishing and Broadcasting and Web Search Portals. That has grown 250% since 2012.
- Electronic retailing, which the Census puts at over $545 billion for (NAICS 4541) electronic shopping and mail order houses. It grew 65% over the same period.

Why else? Digital does not seem to work like other infrastructure.

- **Roads and highways**
  - Finance out of tax $ & heavy users (e.g., gas taxes). Privately financed R&D
  - Largely a gov't function, with occasional self-provision. Occasionally priced toll roads & bridges. Unpriced roads.
  - Cost center for government. Universal service obligations. Coverage of most of country. Many options for drivers.
- **Information super highway**
  - Financed for business interests. Mild subsidies. Private & public R&D
  - Routine private supply & self-provision. Limited military. All priced. No price for open source.
  - Some subsidies, but few geographic obligations. Less in rural areas. Uneven competitive supply.

Why else? Changed a lot in a short time.

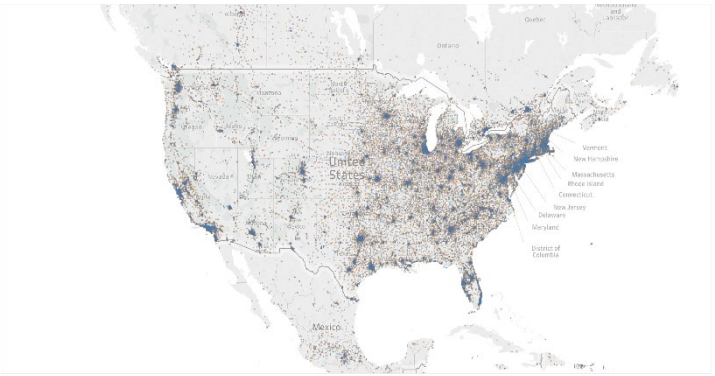
- **Dial-up era, c 2001.**
  - Dial-up domniates.
  - Half households online.
  - Web traffic dominates.
  - Pirated traffic growing.
  - Waiting for 3g.
  - Your grandparents use it for puppy pictures.
  - Concerns about MSFT & Intel & Cisco. Will there be any competition to the biggest platforms?
- **Broadband era, c 2016**
  - Broadband dominates.
  - 75% of HH online.
  - Streaming dominates.
  - OTT & gaming growing
  - Waiting for 5g.
  - Your grandparents use it for cat videos.
  - Concerns about FB, Apple, MSFT, Amazon, Google, Tencent, Ali-Baba. Will there be competition to the biggest platforms?

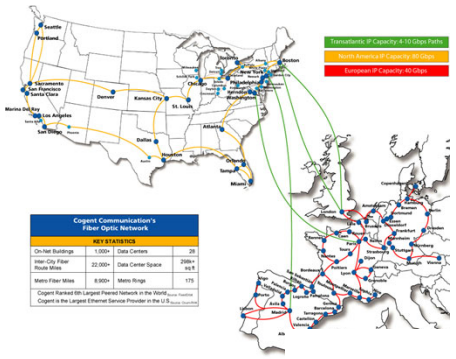
Impressive growth. Digital infrastructure helped, but what role exactly?

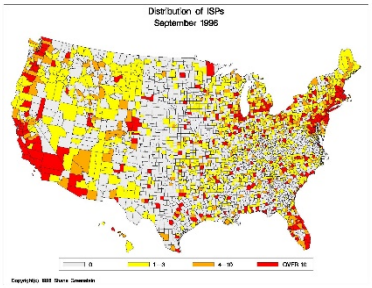
Radio Shack Ad, c 1991.

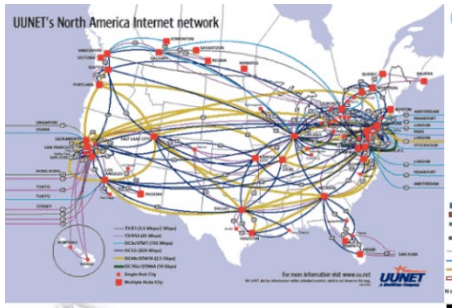
- **Every activity in ad in smart phone.**
  - Record, store, play music & video
  - Take a picture, store it, reproduce.
  - Play a range of games
  - Calculate.
- **And a range of activities not on this ad**
  - Make phone call (w/o wires!).
  - Send/receive email.
  - Check the weather forecast.
  - Access Internet (except throttled streaming).
  - Find best route in traffic.
  - Get on an airplane or venue w/o paper.
  - Get calendar of appointments.

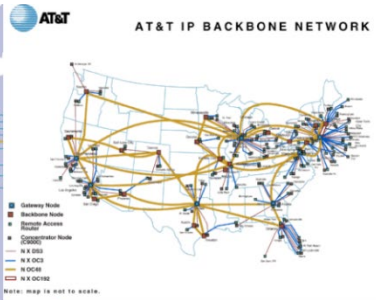
Why else study it? Lots of fun to make and display visuals.

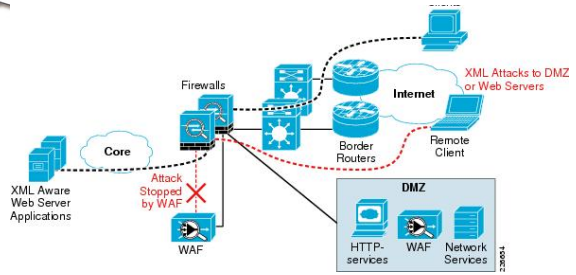


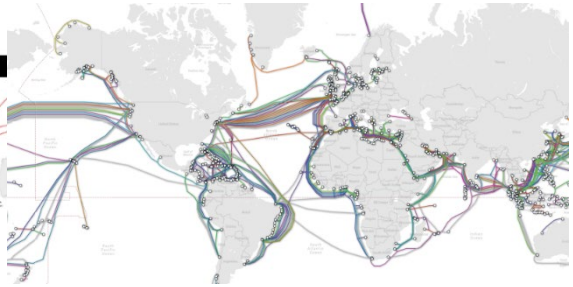










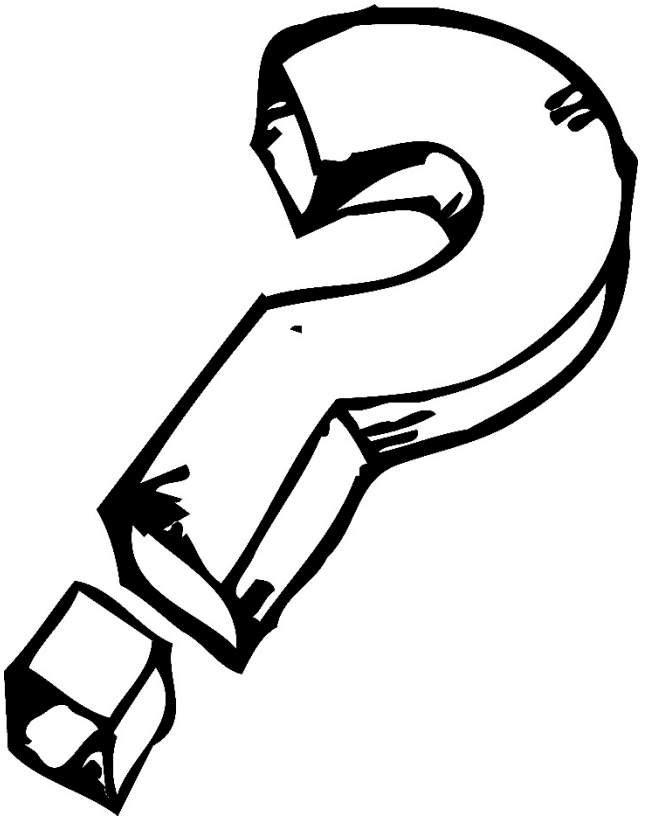


Where is this going?

- Definition of digital infrastructure is a moving target, ranging from narrow to broad. So too are perceptions about the key policy issues.
- Hints at what economic researchers can contribute: defining the question, framing the ideas, and measuring the phenomenon in ways that inform and guide policy discussion.

Brief pause for Q&A

- Any questions?



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  - **The naïve approach**
  - **Rural broadband**
  - **Supply**
  - **Demand**
  - **Opportunities and challenges**

Many researchers intrigued by naïve questions about broadband

- A version of this key question: Should US gov't spend $20 Billion dollars on upgrading rural broadband?
  - What are the economic benefits created by more broadband?
- Why interest in question?
  - Motivation by analogy with telephony, in which many providers received building & operational subsidies from universal service programs.
  - This was an actual proposal for part of 2009 stimulus package (which eventually reached $700B+).

The naïve approach to estimating effect of BB on local economy

- Find data on 3000 US counties. Label as i.
  - Key economic variable: average wage. W_i
  - Determinants: fraction business w/broadband. BB_i
  - Controls: ave est size, density, demograph. X_i
- Regress $W_i = a*BB_i + b*X_i + e_i$
  - Estimate yeilds a >> 0 and significant at 99% level.
  - Next: calculate wage gain from installing broadband.
- What is wrong with that naïve approach?
  - Reverse causality. Prediction? Not valid.

Improving on the naïve approach

- One approach: IV for BB_{it}
  - Estimate a first stage for BB_{it}. But what influences broadband supply but not wages? Good luck.
- Another approach: More data over time.
  - Growth of W_{it} & BB_{it}, then first stage. What influences BB growth & not wage growth? Again, good luck.
  - Diff-in-diff. Matched samples of areas. Exogenous shock on BB installations. Good luck again.
- Conclusion: there is no easy way out.
  - Kolko, 2012, goes as far as possible w/this approach.

Confining the question to rural broadband

- Frontier infrastructure in less dense locations?
  - Again, BB → wages? Naïve approach is problematic.
  - Solution? Compare counties where gov't subsidized broadband w/matched county with no subsidy. Data over time. Wages. Employment. Growth.
- Might work as econometrics, but as economics?
  - Do you expect short-run & measurable response?
  - After years of neglect of low density areas, is that counter-factual relevant any longer?
- Warning: a specialized interest. Read widely.

Ask a different Q: Why more BB in some places and not others?

- Treat market entry/upgrade as endogenous.
  - Seamans, 2012, Cable firms react to threat of municipal entry. (Hint: they upgrade faster.)
  - Connolly, Prieger, 2013, entry/exit rates in BB differ across the country. Some areas more attractive.
  - Skiti, 2019. Anticipated potential entrants → upgrade
- Identification: regions vary in attractiveness.
  - Attractive areas get (1) more providers (b/c more subscribers); & (2) higher bandwidth (b/c ARPU higher). Competition causes what? Hard to separate.

Many approaches to this topic

- If you have enough data at a fine-enough level, control for endogeneity of competitors…
  - Wallsten & Mallahan, 2010: Quality (speed) change when cable faces competitors? Speed increases.
- What about prices? Again, identification issues.
  - Chen & Savage, 2011: western cities with only monopolies or duopolies. How does pricing change w/rival? Price mediated by demand variety.
- Measurement constrained by data.
  - Opportunity? National broadband map?

Do we see market power in user behavior & contracting?

- BB ISPs increasingly offer multi-part pricing
  - Tiers of speeds w/caps on total monthly usage.
  - Interpret as behavior to exploit market power?
- Very detailed data on usage → structural model.
  - Nevo/Turner/Williams, 2016. Shadow value of ceiling → diminished use before monthly cap binds.
  - Malone/Nevo Williams, 2016. Relieve congestion w/peak load pricing, throttling, or caching? (Hint: pricing and caching, not throttling.)
  - Estimate CS, conditional on purchasing access.

A danger w/BB research: Policy interest waxes and wanes.

- US is somewhat unique.
  - In US arose b/c regulators take "facilities-based" approach, & require no interconnection. Questions bargaining power of carriers. Other countries differ.
- Political winds are fickle. Long term issue?
  - For example, recently moved to big app firms.
  - Bargaining b/w big apps & carriers? We know little.
- Moving targets of interest as industry changes
  - Google Fiber or spread of cloud as a natural experiment for diff-on-diff?

Research opportunities associated with demand: consumer surplus

- Generate CS from estimates of demand.
  - Rosston, Savage, Waldman, 2010, demand for attributes. Do infra-marginal users value speed?
  - Greenstein & McDevitt, 2011, use general data on upgrade from dial-up to broadband.
  - Brynjolfsson & Oh, 2012, use value of time online
- Research opportunity: model for access & use?
  - Users pay monthly charges & no usage fees. Users display “plastic” & “bursty” surfing that fills up leisure time. NOT the standard McFadden model.

More new research opportunities associated with BB demand

- Over-The-Top & restructuring of leisure time.
  - Netflix, Sling TV, YouTube TV, HBO Go, & so on.
  - NOT linear TV: Unscheduled; Binge; Variable time.
  - Again, static leisure/labor model just not right approach to estimating how digital alters use.
- No wired telephone, no cable television.
  - What do wireless-only & internet-only households tell us about demand for wireless/BB?
  - Much private interest in this topic. Much public interest in establishing facts/trends.

Long term challenge for research: The price for what service?

- The price index for broadband (in the US) looks all wrong. Has remained flat for ten years.
  - No quality adjustment. Yet, we know speeds went up.
  - CPI defined as price of fixed quality service; does not incorporate value of new service.
- Big opportunities for good price work.
  - E.g., Byrnne et al, 2018, price of cloud declined. Straightforward collection. From scraping internet archive. More possible. Imitatable.
- Issue: price index work is thankless.

What else is missing? Vexing questions w/new opportunities.

- Buyer of broadband gets access to what?
  - Complementary services, but no role in price index.
  - Broadband comes as part of bundled services. No simple price index for data.
- Considerable research on cable firms.
  - Focused on operations behind linear TV viewing.
  - Not (yet) part of conversation about new era.
- Issue: Estimated value of new good? Not really.
  - Lots of room for new models/data on this topic.

Brief pause for Q&A

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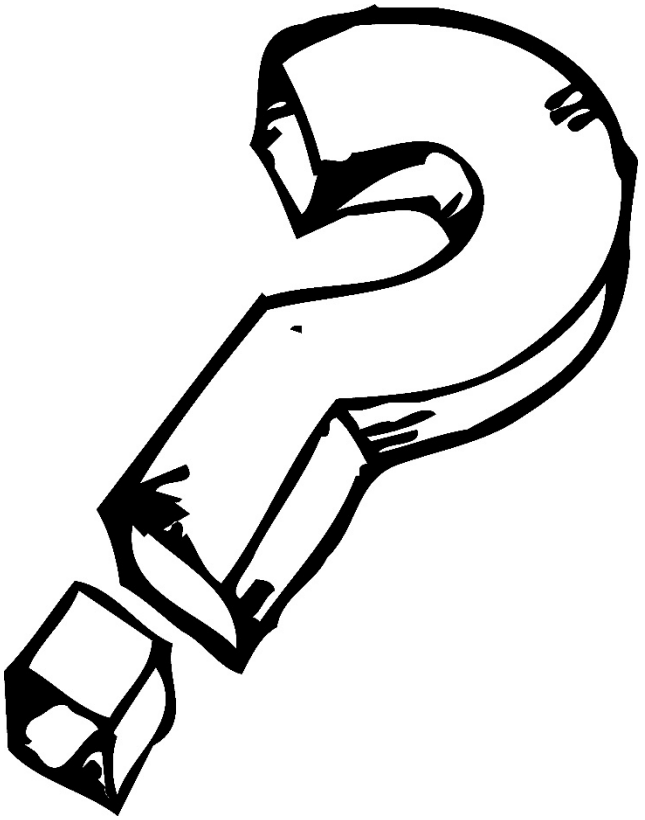

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  - **Broader conceptions of infrastructure.**
  - **Supply.**
  - **Effects.**
  - **Demand.**
  - **Opportunities & challenges.**

Many researchers intrigued by history of internet's origins

- A version of key question: Should US gov't spend $100B on inventing the next big thing (such as the internet)?
  - Should the gov't have spent it in the past? What were the economic benefits created by gov't funded R&D?
  - Note: An ex-post rationalization b/c a close history suggests the economic benefits had little influence on actual behavior. (Greenstein, 2015).
- Calculating economic benefits not easy.
  - Greenstein & Nagle (2014): What if we valued just Apache server? That value alone exceeds known subsidies.
- Despite all caveats, much hunger for research on this topic.

What else motivates a broader conceptions of infrastructure?

- More than BB delivers the internet.
  - Hardware you can see: Data centers, cloud, CDNs, servers, cellular towers, smart phones…
  - But why stop there? Many interconnected pieces – hardware, software, skilled labor.
- Some cities get far better service than others, and many cities get far better service than rural areas.
  - Just as the BB literature splits b/w (1) studies of the determinants of its diffusion & (2) studies of the effect of diffusion on economic activity, so too does the literature examining digital infrastructure split b/w (1) & (2), just broadly construed.

Why do some regions have better infrastructure than others?

- Many complements vary by location.
  - Forman et al (2005): compare business use of basic/advanced internet. Basic almost everywhere, while advanced more frequent in some cities, right industries, etc.
- More opportunities in this line of inquiry.
  - CDNs, cloud, servers, skilled labor, cell towers?
- Key issue: Recognize which margin is identified.
  - Some infrastructure available everywhere, some not. Varies over time. Today, satellite at worse.

What effect does better infrastructure have on activity?

- Regions/cities vary in thickness of supply of the local labor market for skilled labor in software. Interpret as infrastructure of a location.
  - Tambe, 2014, asks: how does the local supply shapes the productivity of firms in those areas?
    - Productivity estimate on use of Hadoop w/interactions of use w/supply conditions for Hadoop programmers. Higher in areas w/better supply. Potential extensions?
  - Forman et al, 2008, asks: Does city provide third party services that substitute for internal provision?
    - Observe in propensity to employ in-house employees.

Does digital infrastructure alleviate or acerbate regional inequality?

- Relate wage growth, etc. Y_i
  - Determinants: Advanced Internet investment, II_i
- Regress $Y_i = a*II_i + b*II_i*X_i + e_i$.
  - Approach: internet generates different outcomes in different places. Exacerbation of regional inequality.
    - E.g., Forman et al, 2012. First difference wage growth 2000 to 1995, w/95 as "start" of the internet. Business adoption of Internet makes rich places richer *& not anywhere else*. But why? Several explanations.
    - Placebo tests. Tests for right timing.
  - More room for extensions of this puzzle.

Challenges w/broad conception: What precisely are we measuring?

- "Regions" = a bundle of factors.
  - Positive correlation of factors: Frontier programmer & IT admins. More local data centers & lines to data exchanges → Identification issues in x-section.
  - Endogenous quality? Nagaraj, 2018: Different quality in regional open street maps? Trace it back to how communities start.
- Recent challenge: geographic association.
  - Cloud has become footloose. It shapes productivity, but difficult to make one-to-one association at a geographic level.

Digital as one of many innovative features of a region

- Delgado et al, 2012, ask: Do regions have different capacity to innovate?
  - Determined by accumulation of private firms action.
  - Capacity of regional infrastructure & digital infrastructure difficult to disentangle.
  - Tied to different levels of entrepreneurial startups and different rates of patenting.
- Pull out different roles of digital infrastructure?
  - Opportunity: Many authors find internet encourages communications & innovative activities. What else?

Underexploited opportunity: wireless access

- Big variance around the US in quality of access over time, over the different carriers.
- Policy interest: What is economic value of new phenomenon (e.g., smart phone, 4G)?
- Wifi also a common access mode. Same question arises.
- Tablets & smart phones diffused into wireless ecosystem, & changed usage, & motivated investments in digital infrastructure. How much?
- Principal challenge for estimating demand: need *own* demand estimate & *substitution* w/alternative forms of wireline access.

Another opportunity? Spectrum as infrastructure?

- Spectrum allocation.
  - Couch it in trad'l economic terms, such as misallocation issues. E.g., Hazlett & Munoz, 2009.
  - Fun topic. (Almost) unbelievable stories of goofy policy.
- From auction data.
  - Participants write about the economic lessons. E.g., Cramton et al, 2011.
- Spectrum value varies by regions, anticipated uses.
  - Changes in value over time. E.g., Connolly et al, 2017.
- Have allocations altered regional experiences?
  - Map US data into regions.
- Big differences around the world in allocation policy.
  - Shapes use? Shapes digital infrastructure? Exogenous factor.

Opportunities? Look one step down from digital infrastructure

- How productivity/behavior of firms changed.
  - Nagle, 2017. Open source software used by US firms.
  - Jin & McElheran, 2019. Cloud use by man'f plants.
  - Ewens et al, 2017. VCs & the cloud? Variable costs decline → more spray and pay models of startups.
  - Gans et al, 2016, mobile/social media changed customer/airline interaction.
  - Reis et al, 2019, Zhang, et al, 2019, time-shift TV viewing, enabled by digital cable. Encourage VOD.
- Growing area of research recently.

More opportunity? Restructuring → network quasi-natural experiments?

- Dispersion of responsibility: Interoperability designs are public; Yet, investment & operations are private. Researchable?
  - Rate of improvement slowing in public organizations? (See e.g., Simcoe, 2012)
- E.g., Smart phones diffusion → demand for equipment & towers, & rise in demand for programmers.
  - Some cities benefit, others not. Which ones? Why?

- Apple, Google, FB, Amazon, MS & vertically integrate into CDNs, fiber?
  - Opportunity for natural experiment?
- What is value of activity displaced by internet?
  - Analysis without stakeholder bias.

Brief pause for Q&A

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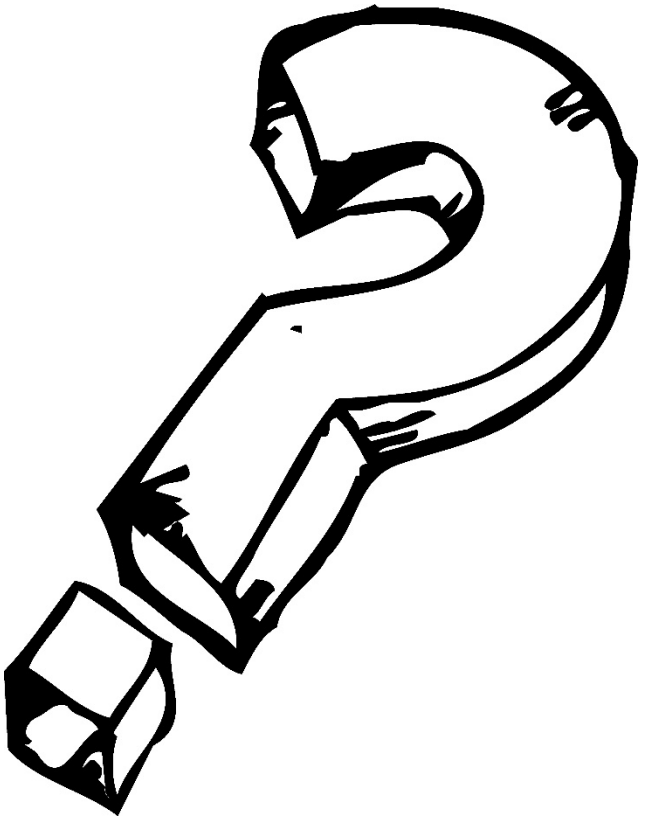

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  - **Natural experiments**
  - **Investment**
  - **Digital measurement**
  - **Opportunities and challenges**

Many researchers intrigued by global policies for digital

- A version of this key question: Should the World Bank lend $10 Billion dollars to upgrade the wireless system in an emerging economy?
  - What are the economic benefits created by digital infrastructure?
  - What has been the payoff in recent past?
- Why interest in question?
  - These type of proposals do, in fact, get made at the World Bank & elsewhere.
  - Emerging economies do, in fact, want to know if such investment are worth the expense.
- Lots of policy interest from OECD, IMF, World Bank, and many NGOs.

What are the bottlenecks to moving forward?

- Int'l statistics available for IT at country level.
  - But US & China dominate many internet mkts.
- Bottlenecks to progress.
  - Only so much variance between 200+ countries.
  - What is identified? Much infrastructure correlated within country. The rich are rich on multiple dimensions, and the poor are poor in everything.
  - Can estimates inform a compelling policy debate?
- Quasi-natural experiments in policy details? Difficulty of keeping up w/details (e.g., EU case).

One agenda: Natural experiments for identifying the effects of digital.

- The UK deployed DSL in a somewhat random way, leaving neighbors w/different service
  - A way to identify the consequence of speed on productivity. (DeStefano et al, 2018).
  - Changes property prices for homes (Ahfeldt, Koutroumpis, Valleti, 2014).
- France & Italy required all gov't agencies use Linux, but only France enforced the decree.
  - Consequences for founding business based on open source? (Nagle, 2019). Yes.

Related agenda: Nat'l experiments in emerging economies

- Africa provides numerous experiments
  - Jonas Hjort and Jonas Poulsen, 2017. When cable was first strung along the African coast. A comparison of firms with access to those without.
  - Daniel Bjorkegren, 2019. Complete data sets of every phone call ever made within a country → direct estimation of network effects.
- Growing field. Advantages & disadvantages.
  - No IRB. Unbelievable detail in datasets. Potential for modeling. Issues with generalizability. Difficult field work. Sometimes idiosyncratic policy settings.

Yet another direction: Endogenize world wide business investment.

- What determines investment in digital infrastructure around the world?
  - Athey and Stern, 2014. Where do operating system users use pirated software and proprietary software? Tension b/w explanations based on "affordability" & "institutions."
  - Ackermann and Greenstein, 2019. Where are the web servers? Which countries have large numbers of open source or not? Affordibility & institutions, plus network quality, & technical sophistication of the local populace.

New direction: Digital enables new measure of economic activity

- Valuable for now-casting in emerging mkts, where GDP measurement apparatus absent.
  - Do geo-located IP addresses give as much information as light from satellite photos? Ackermann et al, 2017, provides evidence.
  - Activity on Twitter (as measured thru GPS-labeled photos) give as much information as the light from satellite photos? Indica, 2018, finds evidence.
- Geographic variance within countries? Yes.
  - Room for matched estimates of cities.

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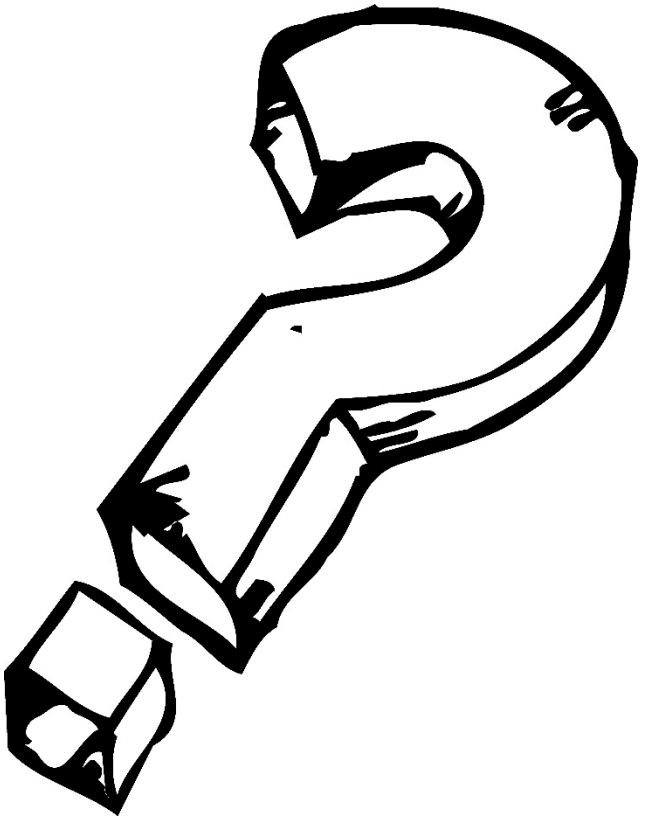

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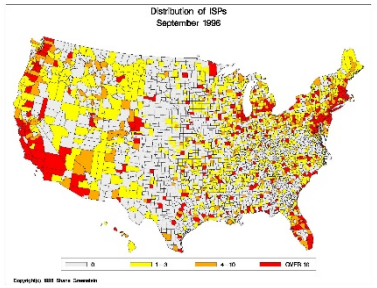
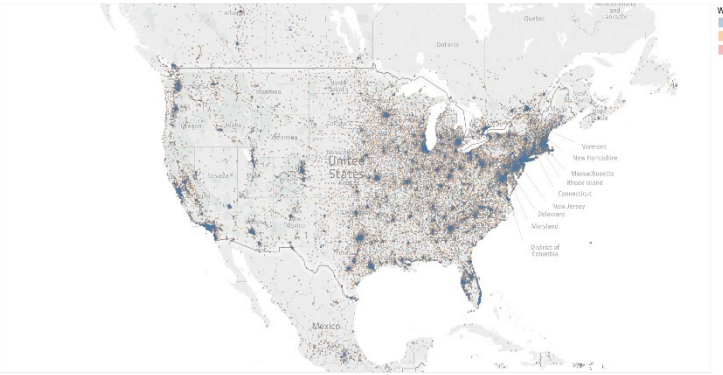
- **Pretentious & avuncular advice**
  - **Policy/profundity tradeoff**
  - **What is neutral?**
  - **Journalists**
  - **Nat'l academies**
  - **Quid-pro-quos**
  - **Testifying**
  - **Trolling**

I have spent much of my career at boundary of academic/policy

- Nobody ever gives you a manual on how to navigate the opportunities and challenges.
- Here are a few reflections on being a neutral policy analyst in a world inhabited (mostly) by advocates.
- FWIW, these are just one person's opinions. There is no right or wrong answer.





First advice: Never lose sight of the policy/profundity trade-off

- Pass on projects destined for A. Allocate your time during tenure clock to B & D. *That's your job.*
- Much policy work falls into C. An occasional project that falls into C is OK, but not too much before tenure. Has to be packaged well at tenure-time.
- Important consideration: Big learning curves in policy research. Can work towards B & D by learning while doing A & C?

Policy & profundity trade-off.	**Not a profound result that academics read or talk about.**	**A profound result that academics read, and talk about.**
No short run impact on firms or policy	A. Most of the time this is what happens to research. *sigh*	B. The senior faculty member in the office next door is happy with you.
Large impact on firms and policy.	C. Intrinsically satisfying, but must be packaged for letter writers so they appreciate.	D. Rare. Worth the trouble when the opportunity arises. Savor the experience.

How to participate in policy research as a neutral academic

- What is neutral? Shorthand for NBER's position.
  - Thou-shall-not-shorthand: never use the phrase… "The government should do x…"
  - Thou-shall-do-shorthand: There is (always) a measurement dimension, & (usually) an identifiable reader (in policy circles) for the facts & analysis.
  - BE AN HONEST BROKER: Fair consideration of POV.
- What is NOT neutral?
  - Motivated reasoning to a predetermined answer, supported by self-interest, ideology, or convenience.

Challenges in feeding policy analysis to journalists

- One challenge: it can put you in the position as "Contrarian economist who obsesses on limits."
  - Firms have $$$ at stake → do not want to hear it.
  - Ideologues have a view → dismissive or unyielding.
  - Can be lonely/unpleasant. Use PR. Use SSRN. Etc.
- Another challenge: no sharp result on Twitter.
  - "On the one hand, on the other hand" ignored.
- But honest journalists do want to find experts.
  - Establish credentials quickly. Be ready w/stories.

When advocates & academics mix at national meetings

- Academics have something advocates lack.
  - Facile use of statistics, visual aides, breadth of facts.
  - Any insight that takes time and depth to assemble.
  - Tenure/gravitas/memory. Your paycheck depends on being right in the long run, not on scoring a “win.”
- Advocates have something the academics lack.
  - Persistence. Charm. Ethics of lawyers. Better budget.
  - Willful/strategic myopia about statistics.
- Remember: reports can inspire.
  - One did for me at an impressionable moment.

Mixing analysts & advocates can be enjoyable or awkward.

- Enjoy conversation at dinner/receptions.
  - My goto phrase: “In your shoes it may appear to be X, but from the outside looking in, it appears to be Y.”
- There are smart people everywhere.
  - Most advocates know stuff. Listen closely. Many are closet intellectuals. Many dislike motivated reasoning & disdain political divisiveness. (Some don’t)
  - Some crave conversation & dialogue. (Some don’t.)
- Be wary if advocates pay. It’s their job to recruit.
  - Before you know it… you “picked a side.” COI applies.

Be thoughtful about picking a side: Quid-pro-quos have consequence

- Quid-pro-quos that work for neutral academics.
  - Walk out with a paper, or unrestricted use of data.
  - Deep understanding of firm & it guides next paper.
  - Temp data mercenary → pay for engagement ring.
- Quid-pro-quos that do not work for academics.
  - Damaged reputation. Conflict of interest that restricts. Waste of time during the tenure clock.
  - Never give a corporate or policy lawyer the right to censor work. Be wary of the unstated conditions.
- Ask questions before agreeing to commitment.

Testifying to Congress: distinguish b/w show and substance.

- Have right expectations.
  - Representatives want to look good. It's their show.
  - Political staff wants to win.
  - Discussion highlights points of (dis)agreement. That's the point!
- Just do it.
  - Goes in the written record.
  - Makes your parents, spouse & friends proud – albeit, not your teenage kids.
- How work mostly gets done.
  - Make efforts to testify at the FTC, FCC, DOJ, CEA, FDA, etc. Agencies do the work.
  - You don't always get credit. Needs to be packaged at tenure-time as "the expert."
- Staff have limited time.
  - They read WSJ, NYT, WP, short pieces in HBR, SMR, VOX, Quartz, some blogs.
  - Write for them!

Political trolling & stalking: a vexing new problem for the digital era.

- Congrats! You know you reached the big leagues when the crazies start paying attention to you.
- First act: apologize to the IT dep't after your post brings down university's servers.
  - You need them on your side.
- Can be unpleasant. Hard to know what is right thing to do.
  - Don't face it alone. Involve dep't chair, dean, research admin.
  - Early involvement is better.
- *If you can,* ignore sound & fury.
  - Beware of Streisand effect. (i.e., bringing awareness to it invites more unwanted attention).
  - Sometimes it can die on its own.
- If it gets ugly, engage police & lawyers for university.

Thanks for your attention

- We are done.
- Any questions?