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Sunny with a chance of traffic: Government intervention and its effects on knowledge accumulation in science and industry

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Sunny with a chance of traffic: Government intervention and its effects on knowledge accumulation in science and industry

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by

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ABSTRACT OF THE DISSERTATION

Sunny with a chance of traffic:
Government intervention and its effects on knowledge
accumulation in science and industry

by

Andrew Christopher Herman
Doctor of Philosophy in Sociology
University of California, Los Angeles, 2022
Professor Rebecca J. Emigh, Chair

It is frequently asserted that government intervention around science and R&D disrupts the efficient search for knowledge. The main argument in this dissertation is that while governments do have considerable power to influence what topics scientists choose to work on, government intervention does not slow the accumulation of knowledge, and in some cases accelerates it. Two historical case studies illustrate this point, one around weather forecasting and the other around in-vehicle road navigation, both set in the mid-

20th century in the United States. Because the federal government was a consistent sponsor of weather forecasting research, while also withdrawing its support from in-vehicle road navigation technology by the early 1970s, the two cases provide analytical leverage to draw out the specific mechanisms that linked government action to the accumulation of knowledge in science and industry.

Historically speaking, the differences in how government engaged with the two domains meant that weather forecasting research continued to flourish despite low accuracy, while in-vehicle road navigation technology was delayed for nearly thirty years until GPS re-energized the space in the mid-1990s. Government decision-making was crucial in establishing these long-term trajectories. But nonetheless, factors around the diffusion process outstripped the government's ability to impact scientists' choice of research topics with each new intervention. Even in situations where the government made bad investments into technology, scientists quickly redirected their efforts toward more fruitful applications. Science continued to efficiently search for knowledge in the presence of government intervention.

The distortionary impacts of government intervention are thus overstated in the literature, not to mention in public discourse. Over and above this, though, by providing key technology to scientists, government intervention unlocked new possibilities for research. With weather forecasting and in-vehicle road navigation, the government shaped the accumulation of knowledge less by making science inefficient and more by overcoming the obstacles blocking the way for certain lines of research.

The dissertation of Andrew Christopher Herman is approved.

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Gomez, C. J., Herman, A. C., & Parigi, P. (2020). Moving more, but closer: Mapping the growing regionalization of global scientific mobility using ORCID. *Journal of Informetrics*, 14(3), 101044. https://doi.org/10.1016/j.joi.2020.101044

Herman, A. C. (2020). Fascists at the fair: Political resistance at the 1933–1934 Chicago World's Fair. *Journal of Historical Sociology*, *33*(2), 198–215. https://doi.org/10.1111/johs.12269

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VanWynsberghe, R., & Herman, A. C. (2015). Education for social change and pragmatist theory: five features of educative environments designed for social change. *International Journal of Lifelong Education*, *34*(3), 268–283. https://doi.org/10.1080/02601370.2014.988189

Chapter 1:

Introduction

Innovation and government

Social scientists have recognized that innovation spurs economic growth since at least the early 20th century, thanks to the work of a pair of German economists. The first was Werner Sombart,[1] who coined the term "creative destruction" to describe the way that competition and economic constraint drove innovation. Joseph Schumpeter followed closely after, explaining that capitalism was in fact defined by a cycle of creative destruction where new ideas, products, and companies would replace old ones, growing the economy in the process.[2] These ideas have taken on even greater importance over the past generation of social scientists, as scholars like Paul Romer incorporated technological innovation and human capital into macro-economic models of growth.[3]

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[1] Werner Sombart, Der Moderne Kaptalismus, (München & Leipzig: Duncker & Humblot, 1927 [1902]).

[2] Joseph A. Schumpeter, Capitalism, Socialism, and Democracy, 3rd edn (New York: Harper & Brothers Publishers, 1950 [1942]).

[3] Paul M. Romer, 'Endogenous Technological Change', *Journal of Political Economy*, 98.5 (1990), 71–102 <https://doi.org/10.1086/261725>; Paul M. Romer, 'Increasing Returns and Long-Run Growth', *Journal of Political Economy*, 94.5 (1986), 1002–37; Paul M. Romer, 'Growth Based on Increasing Returns Due to Specialization', *The American Economic Review*, 77.2 (1987), 56–62. See also Philippe Aghion and Peter Howitt, 'A Model of Growth Through Creative Destruction', *Econometrica*, 60.2 (1992), 323–51; Philippe Aghion, Ufuk Akcigit, and Peter Howitt, 'What Do We Learn From Schumpeterian Growth Theory?', in *Handbook of Economic Growth* (Elsevier B.V., 2014), II, 515–63 <https://doi.org/10.1016/B978-0-444-53540-5.00001-X>.

Markets are taken to be the conduit for creative destruction and the innovation that comes along with it. For this reason, the most common refrain in economic theory and policy circles has been to ask governments to interfere as little as possible, so as to let the mechanisms of creative destruction work to their full effect.

But governments have their own unique impact on the economy. Among other things, they are one of the very few institutions that can coerce people and businesses in markets to follow the rules,[4] they have a much higher capacity to take risks compared to industry,[5] and they can motivate people by appealing to national pride or simply self-preservation. These facts have made governments the focus of a lot of scientific research into innovation and economic growth. Governments are said to make markets, protect them, disrupt them, and undermine them.[6]

One of the most common ways to approach the question of how governments affect innovation is to point at the monumental success of large-scale government science projects during the Second World War and in the two decades that followed.[7] On the face of

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[4] Douglass C. North, *Institutions, Institutional Change and Economic Performance* (New York: Cambridge University Press, 1990) <https://doi.org/10.1017/cbo9780511528118.012>.

[5] Mariana Mazzucato, 'Financing Innovation: Creative Destruction vs. Destructive Creation', *Industrial and Corporate Change*, 22.4 (2013), 851–67 <https://doi.org/10.1093/icc/dtt025>; Mariana Mazzucato and Gregor Semieniuk, 'Public Financing of Innovation: New Questions', *Oxford Review of Economic Policy*, 33.1 (2017), 24–48 <https://doi.org/10.1093/oxrep/grw036>; William Lazonick and Mariana Mazzucato, 'The Risk-Reward Nexus in the Innovation-Inequality Relationship: Who Takes the Risks? Who Gets the Rewards?', *Industrial and Corporate Change*, 22.4 (2013), 1093–1128 <https://doi.org/10.1093/icc/dtt019>.

[6] Karl Polanyi, *The Great Transformation* (Boston, MA: Beacon Press, 2001); Peter Evans, *Embedded Autonomy: States and Industrial Transformation* (Princeton, N.J.: Princeton University Press, 1995); Fred Block, 'Swimming against the Current: The Rise of a Hidden Developmental State in the United States', *Politics and Society*, 36.2 (2008), 169–206 <https://doi.org/10.1177/0032329208318731>.

[7] Block; D. Foray, D. C. Mowery, and R. R. Nelson, 'Public R&D and Social Challenges: What Lessons from Mission R&D Programs?', *Research Policy*, 41.10 (2012), 1697–1702 <https://doi.org/10.1016/j.respol.2012.07.011>; David C. Mowery, 'National Security and National

it, there is a lot of appeal in this line of thinking. The human genome project, computers, the internet, satellites, even microwaves and memory foam are all products of research done by the military or at NASA during this period.

The trouble is that deciding how much credit government deserves for this or that innovation is far from trivial. In the absence of the space race, maybe businesses would have still brought memory foam to the market and provided geolocation services. This would mean that government was not all that influential, after all. Of course, scientists can't manipulate and control history like they can the chemicals in a test tube, so this problem stands unresolved.

Also unresolved is the related question of how much credit governments deserve for innovation downstream. Do innovations that draw on government-funded research count in the government's favor? Or is the cumulative effect of government involvement irrelevant? To put it glibly, how much credit does the government deserve every time someone warms up a frozen dinner in the microwave?

The economist Nathan Rosenberg pointed out these issues back in 1969.[8] But the fundamental difficulty has not gone away. For example, exactly fifty years later in 2019, one team of leading researchers touted that "government-funded research increasingly fuels

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Innovation Systems', *Journal of Technology Transfer*, 34.5 (2009), 455–73 <https://doi.org/10.1007/s10961-008-9100-4>; Mazzucato, 'Financing Innovation: Creative Destruction vs. Destructive Creation'; Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1990); Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge, MA: MIT Press, 1997); Richard R. Nelson, *The Moon and The Ghetto: An Essay on Public Policy Analysis* (New York: W. W. Norton and Company, 1977).

[8] Nathan Rosenberg, 'The Direction of Technological Change: Inducement Mechanisms and Focusing Devices', *Economic Development and Cultural Change*, 18.1 (1969), 1–24 <https://www.jstor.org/stable/1152198>.

innovation."[9] Another team of equally eminent figures wrote in that same year, that "the U.S. government invests more than $50 billion per year in R&D procurement but we know little about the outcomes of these investments."[10] Half a century has gone by with virtually no progress toward a consensus—even on the question of how to count up the value of a government investment.

The lack of an accepted answer has done nothing to slow interest in this sort of large-scale government action. The EU launched the "Horizon Europe" program in 2021, in the hopes of increasing science spending within the union by 50% by 2027. Much of this investment is being modeled on the mission-oriented innovation policy championed by scholars like Mariana Mazzucato,[11] and explicitly evokes the memory of the Apollo Missions as the justification for large-scale government action. Horizon Europe is oriented around five such missions: adaptation to climate change, climate-neutral and smart cities, cancer, healthy soil, and the restoration of oceans and waters. In the United States the Biden administration announced in early 2022 the "Moonshot 2.0" plan to reduce the cancer death rate by at least 50% over the next 25 years. The Democratic Party's proposed "Green New Deal" is another example of large-scale, mission-oriented innovation policy. China's

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[9] L. Fleming and others, 'Government-Funded Research Increasingly Fuels Innovation', *Science*, 364.6446 (2019), 1139–41 <https://doi.org/10.1126/science.aaw2373>.

[10] Gaétan De Rassenfosse, Adam Jaffe, and Emilio Raiteri, 'The Procurement of Innovation by the U.S. Government', *PLoS ONE*, 14.8 (2019) <https://doi.org/10.1371/journal.pone.0218927>.

[11] Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths* (London: Anthem Press, 2013).

National Medium and Long-Term Plan for the Development of Science Technology is yet another example.

This dissertation is an attempt to circumvent the standstill in understanding how governments affect innovation in the long-term. I tell the history of government involvement in R&D around weather forecasting and in-vehicle road navigation in this period from the Second World War to the mid-1970s. My goal is not to establish how much value there was in the government's interventions, but instead to identify some key mechanisms that allow governments to impact R&D over the long run, and their main limiting factors. For policymakers this means setting reasonable expectations for what governments can accomplish at the very height of their interventionist powers.

How innovation accumulates

How innovation accumulates

Around the same time that Schumpeter was developing his ideas about creative destruction and economic growth, Seabury Gilfillan, his American pen pal at Columbia University and Chicago's Museum of Science and Industry,[12] was articulating his own theory of technology. A sociologist by training, rather than being motivated by concerns around economic growth like Schumpeter, Gilfillan was more interested in the social processes that lead to and stem from innovation.[13] He enumerated fully 38 social principles

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[12] Matthieu Ballandonne, 'Eugenics and the Interwar Approach to Inventors and Invention: The Case of Seabury Gilfillan', *History of Political Economy*, 53.1 (2021), 1–34 <https://doi.org/10.1215/00182702-8816589>.

[13] S. C. Gilfillan, *The Sociology of Invention* (Chicago: Follett Publishing Company, 1935); S. C. Gilfillan, *Inventing the Ship* (Chicago: Follett Publishing Company, 1935).

of invention. Most of these principles are off topic for the present study, but his first three principles introduce the main theoretical idea that I want to bring up. They emphasize first, that invention is a process of accretion, where little details add together over time in an evolutionary process, second that technologies are combination of elements, and finally that inventions represent new combinations of already existing elements.[14]

Gilfillan was not alone in pursuing this line of research. His colleague and sometimes collaborator in Chicago, William Ogburn, repeated many of the same of ideas about the combinatorial nature of technology and pioneered the effort to forecast the impacts of new technologies on society.[15] The economist Abbott Usher was making similar claims as well.[16] While Schumpeter was occupied with explaining how technological innovation impacted economic growth, these researchers found their foil in great man theories of history, where inventions were credited to genius. By highlighting that technologies were combinations of earlier ideas, that the elements of technology accumulate over time, and that it all works through a slow evolutionary process, Gilfillan, Ogburn, Usher, and others, were pushing back and arguing instead that innovation was a social process much larger than any single person.

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[14] Gilfillan, *The Sociology of Invention*, pp. 5–6.

[15] e.g. William Fielding Ogburn, 'Technology and Society', *Social Forces*, 17.1 (1938), 1–8 <https://www.jstor.org/stable/2571141>; For a detailed overview on Ogburn's contribution to the area, see Benoît Godin, 'Innovation Without the Word: William F. Ogburn's Contribution to the Study of Technological Innovation', *Minerva*, 48.3 (2010), 277–307 <https://www.jstor.org/stable/41821527>.

[16] Abbott P. Usher, *A History of Mechanical Inventions* (New York: Dover, 1929).

The mythology that still surrounds figures like Steve Jobs and Elon Musk shows that great man theories were never truly displaced in the public imagination, but the larger point about the nature of technology has had a lasting effect among scholars. Seen historically, the evolution of technology is a branching path where a particular combination of elements is chosen to develop the next technology, and necessarily, some combinations are left unexplored.

The fact that technology evolves along a branching path immediately raises the specter of the old question in economics, of whether the government is any good at picking and choosing winners. But the affinity goes deeper than this. To understand the broader set of mechanisms that governments initiate when they try to affect innovation, there needs to be more consideration of how researchers, themselves, pick and choose the projects they work on.

With that in mind, back in the 1960s philosophers of science began to realize that community norms played a big role in determining the direction that scientific progress took. For Kuhn this was an issue of what he called paradigms, the set of problems that the scientific community agreed upon as being important, and the set of techniques or approaches that the scientific community believed could be fruitful.[17] In normal times, science would make remarkable progress thanks to the coordination that paradigms made possible, though that progress came along the trajectories that the prevailing paradigm defined as being important. Eventually the paradigm would be overturned by new research

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[17] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962) <https://doi.org/10.7208/chicago/9780226458106.001.0001>.

or by generational turnover,[18] prompting new lines of inquiry and a new consensus. Scientists appeared to choose their research projects according to norms and tradition.

These norms and traditions may or not may not be rationally grounded. In suggesting that scientific revolutions come not just from “revolutionary” research, but when the defenders of the old regime retire or pass away, Kuhn indicated that to a significant degree, scientific progress did not come from some rational idea, but through larger—and perhaps irrational, by comparison—social processes. But this is not the only way to explain the transition from one trajectory to the next. Lakatos pushed back, arguing that research programs in science were held together not by personnel and inertia but by the heuristics scientists use to choose projects.[19] Some heuristics tell scientists to avoid certain topics while others highlight the specific problems that ought to be solved next.[20]

The philosophical debate over the (ir)rationality of the scientific enterprise is less important than the empirical reality of how the direction is decided for the accumulation of knowledge. History shows that several factors have affected the trajectory of science. New technologies open new lines of investigation, whether by providing new capabilities[21] or

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[18] The generational turnover argument was bolstered recently by a wonderful study, namely, Pierre Azoulay, Christian Fons-Rosen, and Joshua S. Graff Zivin, ‘Does Science Advance One Funeral at a Time?’, *American Economic Review*, 109.8 (2019), 2889–2920 <https://doi.org/10.1257/aer.20161574>.

[19] Imre Lakatos, ‘Criticism and the Methodology of Scientific Research Programmes’, *Proceedings of the Aristotelian Society*, 69 (1968), 149–86 <https://www.jstor.org/stable/4544774>.

[20] Lakatos believed that framing the issue of problem selection in science as a matter of negative and positive heuristics provided a rational basis for how knowledge accumulated and avoided the irrational tenor of Kuhn’s account.

[21] Hannah Landecker, ‘Seeing Things: From Microcinematography to Live Cell Imaging’, *Nature Methods*, 6.10 (2009), 707–9 <https://doi.org/10.1038/nmeth1009-707>; Mario Coccia, ‘The Evolution of Scientific

posing new problems,[22] tightly woven research communities provide coordination to keep knowledge accumulation moving in particular directions,[23] important figures centralize research topics, and their death creates room for new ideas to take hold in the scientific consciousness,[24] scarce resources induce researchers to pursue topics that are more likely to get funded,[25] and published statements (true or false) create momentum in how other scientists conceive of their research problems.[26]

Many of the same mechanisms for choosing research trajectories are at work around technology. The main differentiator for the matter of technological innovation is that while science has insulated itself to a significant extent from market forces, pursuing knowledge for knowledge's sake, invention is much harder to disentangle from consumers. At least in market economies, individual inventors and industrial labs are more willing to pursue new

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Disciplines in Applied Sciences: Dynamics and Empirical Properties of Experimental Physics', *Scientometrics*, 124.1 (2020), 451–87 <https://doi.org/10.1007/s11192-020-03464-y>.

[22] W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (New York: Free Press, 2009); Rosenberg.

[23] Steven S. Seidman, 'Models of Scientific Development in Sociology', *Humboldt Journal of Social Relations*, 15.1 (1987), 119–39; Karin Knorr Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, Massachusetts: Harvard University Press, 1999); Edward A. Tiryakian, 'The Significance of Schools in the Development of Sociology', in *Contemporary Issues in Theory and Research*, ed. by W.E. Sniezk, R. Fuhrman, and M.K. Miller (Westport, CT: Greenwood Press, 1979), pp. 211–33.

[24] Kuhn, *Struct. Sci. Revolutions*; Azoulay, Fons-Rosen, and Zivin.

[25] Grit Laudel, 'The Art of Getting Funded: How Scientists Adapt to Their Funding Conditions', *Science and Public Policy*, 33.7 (2006), 489–504 <https://doi.org/10.3152/147154306781778777>; Karin Knorr-Cetina, *The Manufacture of Knowledge: An Essay on the Constructivist and Contextual Nature of Science* (Oxford: Pergamon Press, 1981).

[26] Andrey Rzhetsky, Ivan Iossifov, and others, 'Microparadigms: Chains of Collective Reasoning in Publications about Molecular Interactions.', *Proceedings of the National Academy of Sciences of the United States of America*, 103.13 (2006), 4940–45 <https://doi.org/10.1073/pnas.0600591103>; Silas Boye Nissen and others, 'Publication Bias and the Canonization of False Facts', *ELife*, 5.DECEMBER2016 (2016), 1–19 <https://doi.org/10.7554/eLife.21451>.

ideas when they believe that there is consumer demand.[27] This is not to say that technology is without internal dynamics, only that they intermingle with the pull from market forces.[28]

Giovanni Dosi has adapted ideas from Kuhn and Lakatos to explain how this all works.[29] Industrial R&D and applied research in universities operate according to their own paradigms, with researchers sharing an idea of what problems are worth pursuing and what methods offer the most promising solutions. Technological paradigms, like scientific paradigms, let researchers make lots of progress along specific trajectories thanks to concentrated resources and effort. This does mean, however, that there are always methods and problems that languish in the background because they are not prioritized in the prevailing paradigm. As with science, the evolution of technology is an issue of which trajectories it follows.

This has added importance because of the cumulative nature of technology. Each new innovation builds on the old, allowing the selection of one evolutionary path over another to bring a snowball effect that increases the rate of innovation around nearby problems at

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[27] David Mowery and Nathan Rosenberg, 'The Influence of Market Demand upon Innovation: A Critical Review of Some Recent Empirical Studies', *Research Policy*, 8 (1979), 102–53 <https://doi.org/10.1017/cbo9780511611940.011>; W. Brian Arthur, 'The Structure of Invention', *Research Policy*, 36.2 (2007), 274–87 <https://doi.org/10.1016/j.respol.2006.11.005>; James A. Evans, 'Industry Induces Academic Science to Know Less about More', *American Journal of Sociology*, 116.2 (2010), 389–452.

[28] Chris Freeman and Luc Soete, *The Economics of Industrial Innovation*, 3rd edn (Cambridge, MA: MIT Press, 1997).

[29] Giovanni Dosi, 'Technological Paradigms and Technological Trajectories A Suggested Interpretation of the Determinants and Directions of Technical Change', *Research Policy*, 11.3 (1982), 147–62 <https://doi.org/10.1016/0048-7333(82)90016-6>; Donald MacKenzie, 'Economic and Sociological Explanations of Technological Change', in *Knowing Machines: Essays on Technical Change* (Cambridge, MA: MIT Press, 1998), pp. 49–66 <https://doi.org/https://doi.org/10.7551/mitpress/4064.003.0004>.

the expense of problems that farther away.[30] The result is that researchers and firms can often find more value from exploiting an existing trajectory of research than by exploring for innovations in other areas, making it difficult to switch back once the process gains speed. The same difficulty in switching between research trajectories occurs as technology is integrated more fully into social life and the built environment. This gives technology a certain momentum, making it difficult and costly to switch from one line of inquiry to another—both from a monetary and social perspective.[31] Importantly, as Donald MacKenzie explains, research trajectories can be likened to an institution. Like other institutions research trajectories do not succeed or fail just on the basis of their internal logic, but because of vested interests and the basic expectations that the trajectory will continue.[32] Whatever momentum technologies have comes from the social relationships and beliefs that sustain them.

What this sort of technological momentum also means is that the mechanisms that influence what researchers decide to work on—that determine research trajectories—are different when technologies are just being introduced and when they are more mature. Mature technologies are more subject to basic economic forces. Demand, as perceived

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[30] Daron Acemoglu, Ufuk Akcigit, and William R. Kerr, 'Innovation Network', *Proceedings of the National Academy of Sciences*, 113.41 (2016), 11483–88 <https://doi.org/10.1073/pnas.1613559113>; Lee Fleming, 'Recombinant Uncertainty in Technological Search', *Management Science*, 47.1 (2001), 117–32 <https://doi.org/10.1287/mnsc.47.1.117.10671>; Lee Fleming and Olav Sorenson, 'Technology as a Complex Adaptive System: Evidence from Patent Data', *Research Policy*, 30.7 (2001), 1019–39 <https://doi.org/10.1016/S0048-7333(00)00135-9>.

[31] Thomas P. Hughes, 'Technological Momentum in History: Hydrogenation in Germany 1898-1933', *Past and Present*, 44.1 (1969), 106–32 <https://doi.org/10.1093/past/44.1.106>; Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880--1930* (Baltimore: Johns Hopkins University Press, 1983).

[32] MacKenzie, 'Economic and Sociological Explanations of Technological Change'.

through market research and forecasting, largely determines R&D investment and the types of projects that industrial labs pursue.[33] What's more, R&D is insulated from alternative research trajectories thanks to how deeply mature technology is embedded into social life. Switching to alternative technologies is costly because of how taken for granted it has become in social life. Routines, rituals, and accumulated skills would need to be upended in order to transition to something else, no matter how promising the alternative.[34]

New technologies, by contrast, do not have the benefit of market information about demand, nor are they protected from alternative research trajectories by widespread social uptake. They are inherently uncertain and risky. For these technologies, institutional factors matter more in determining the trajectory of R&D. Research trajectories are more likely to be chosen as a result of the accumulated expertise in scientific fields and industrial labs,[35] and the economic incentive structure around innovation finance.

Alongside the institutional factors that affect the R&D trajectories around new technologies, social discourse defines how a new technology will be used, what its appropriate limits should be, and how it will fit into the larger social system.[36] Rather than

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[33] Dosi, pp. 153–57; Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Belknap Press, 1982).

[34] Paul A. David, 'Clio and the Economics of QWERTY', *The American Economic Review*, 75.2 (1985), 332–37 <https://www.jstor.org/stable/1805621>; George Basalla, *The Evolution of Technology* (New York: Cambridge University Press, 1988).

[35] Dosi, p. 155.

[36] Michel Callon, 'Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay', in *Power, Action and Belief: A New Sociology of Knowledge*, ed. by John Law (London: Routledge, 1986), pp. 196–223; John Law and Michel Callon, 'Engineering and Sociology in a Military Aircraft Project : A Network Analysis of Technological Change', *Social Problems*, 35.3 (1988), 284–97;

an question of engineering, this process lies at the intersection of social life and politics, with controversies being settled by who is able to wrangle the most (and the best) allies,[37] and which perspective poses the most insurmountable obstacles. How controversies and disagreements get resolved shift research teams from one focus to another as it becomes clear that specific trajectories have lost out. This same process shapes emerging markets.

Once again, as with the institutional factors affecting R&D, the social discourse around a technology matters mainly in the early part of its history. After initial controversies are resolved technologies increasingly become taken for granted parts of the social environment.[38] The same sort of technological momentum takes over at this point, with technologies becoming increasingly locked-in and the research trajectories around them

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Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge, Massachusetts: Harvard University Press, 1987); Bruno Latour, *The Pasteurization of France* (Cambridge, MA: Harvard University Press, 1993).

[37] Madeleine Akrich, Michel Callon, and Bruno Latour, 'The Key to Success in Innovation Part I: The Art of Interessement', *International Journal of Innovation Management*, 6.2 (2002), 187–206 <https://doi.org/10.1142/S1363919602000550>; Madeleine Akrich, Michel Callon, and Bruno Latour, 'The Key to Success in Innovation, Part II: The Art of Choosing Good Spokespersons', *International Journal of Innovation Management*, 6.2 (2002), 207–25 <https://doi.org/10.1142/S1363919602000562>; Susan Leigh Star and James R. Griesemer, 'Institutional Ecology, "translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39.', *Social Studies of Science*, 19.3 (1989), 387–420 <https://doi.org/10.1177/030631289019003001>; Trevor J. Pinch and Wiebe E. Bijker, 'The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other', *Social Studies of Science*, 14 (1984), 339–441; Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechical Change* (Cambridge, MA: MIT Press, 1995).

[38] F.W. Geels, 'The Dynamics of Transitions in Socio-Technical Systems: A Multi-Level Analysis of the Transition Pathway from Horse-Drawn Carriages to Automobiles (1860-1930)', *Technology Analysis and Strategic Management*, 17.4 (2005), 445–76 <https://doi.org/10.1080/09537320500357319>; Hughes, 'Technological Momentum in History: Hydrogenation in Germany 1898-1933'.

following suit. Technological trajectories become irreversible as society converges on an understanding of how they ought to be used.[39]

We can see, then, that the evolution of technology is characterized by a series of historical junctures where one path is chosen over another, producing a snowball effect in the long run. This may owe to the accumulation of expertise along some trajectories over others, and to the overarching paradigms that define which problems are worth pursuing and what solutions are the most promising. It is equally influenced by market demand, and the societal discourse around what a technology should become.

The idea that governments pick and choose, not just technologies but entire research trajectories, fits neatly with this understanding of technology. But it is not enough to simply identify the affinity, as the debate in political economy has tended to do. If the government impacts the evolution of technology, which mechanisms does it work through, and when do those mechanisms become operative?

Governments and innovation

Accompanying the demand that governments take a hands-off approach toward innovation is the reality that markets—even the most competitive ones—have long been known to produce less innovation than would be ideal for economic growth.[40] On the one hand, because knowledge is non-rivalrous, that is, available to everyone once it emerges, there is

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[39] Michel Callon, 'The Dynamics of Techno-Economic Networks', in *Technological Change and Company Strategies*, ed. by Rod Coombs, Paolo Saviotti, and Vivien Walsh (London: Academic Press, 1992), pp. 72–102.

[40] e.g. see Kevin A. Bryan and Heidi L. Williams, 'Innovation: Market Failures and Public Policies', *NBER Working Paper Series*, 29173 (2021), 1–96.

little to stop competitors from profiting off the same idea without needing to make the same R&D investments that the innovator needed to pay. This is of course bad for innovators. But it is a boon for society at large, since more knowledge and more technological components means that firms have new combinations to explore, leading to more and better products and services in the long run.

On the other hand, even when patent rights are guaranteed so as to provide some incentive for innovators despite the non-rivalry of knowledge, they create temporary monopolies that themselves have the effect of slowing down innovation. Licensing negotiations can make it difficult to use certain components in new technology, and firms with a lot of patents in a single area can further reduce innovation by forcing virtually every line of inquiry to run through the company's intellectual property.[41] In the reverse of the first scenario, the patent system is a boon for innovators and likely bad for society at large, at least to the extent that it limits the spillover potential of new knowledge.

Despite the common refrain that governments should remain hands-off, markets themselves fail to provide the right set of incentives in many cases. As a consequence, it has long been standard policy for decades for governments to step in when market failures occur. They may assist small and medium sizes businesses in covering transaction costs that would otherwise be prohibitive and provide support for venture capital markets. Or

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[41] Georg Von Graevenitz, Stefan Wagner, and Dietmar Harhoff, 'Incidence and Growth of Patent Thickets: The Impact of Technological Opportunities and Complexity', *Journal of Industrial Economics*, 61.3 (2013), 521–63 <https://doi.org/10.1111/joie.12032>; James Bessen, 'Patent Thickets: Strategic Patenting of Complex Technologies', *SSRN Electronic Journal*, 2003 <https://doi.org/Bessen, James E., Patent Thickets: Strategic Patenting of Complex Technologies (March 2003). Available at SSRN: https://ssrn.com/abstract=327760 or http://dx.doi.org/10.2139/ssrn.327760>.

for high-cost and high-risk goods, government may take on the task of purchasing and implementing the technology itself.[42]

Since the financial collapse in 2008 another rationale has emerged for government intervention around innovation. Rather than constraining the role of government to address only situations where market mechanisms fail, it suggests that governments can direct the economy to solve the grand challenges that society faces at any given time.[43] In this view, some societal problems are dire enough to merit large-scale government intervention, whether it undermines the efficiency of market mechanisms or not. Climate change and the green energy transition are the most common examples.

This view is still largely aspiration. But the reality of government involvement around innovation is more complex than economic theory normally allows. Government has used a heavy hand in guiding military R&D for centuries, but since right around the time of the Second World War, it has increasingly taken on the role of a coordinator in an increasingly complex economic scene.

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[42] Stephen Martin and John T. Scott, 'The Nature of Innovation Market Failure and the Design of Public Support for Private Innovation', *Research Policy*, 29 (2000), 436–47 <https://doi.org/10.1016/S0048-7333(99)00084-0>.

[43] Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*; Mariana Mazzucato, 'From Market Fixing to Market-Creating: A New Framework for Innovation Policy', *Industry and Innovation*, 23.2 (2016), 140–56 <https://doi.org/10.1080/13662716.2016.1146124>; Stefan Kuhlmann and Arie Rip, 'Next-Generation Innovation Policy and Grand Challenges', *Science and Public Policy*, 45.4 (2018), 448–54 <https://doi.org/10.1093/SCIPOL/SCY011>; David C. Mowery, 'Defense-Related R&D as a Model for "Grand Challenges" Technology Policies', *Research Policy*, 41.10 (2012), 1703–15 <https://doi.org/10.1016/j.respol.2012.03.027>.

As Hughes has explained, the organization of innovative work changed dramatically in the United States starting in the late 19th century.[44] At the time inventors worked independently for the most part, tinkering with whatever components they had available. In the first two decades of the 20th century, scientific management and the factory line industrialized innovation. Companies like Bell and DuPont created laboratories staffed with scientists pursuing a combination of basic and applied research. Government followed closely behind, establishing large research laboratories under the purview of the military. These developments simply scaled up the earlier tendency for governments to exert direct control over a wide swath of scientific research.

The Second World War brought with it the beginnings of the triple-helix of science, the complex network of connections that run between universities, industry, and government, in the work of innovation.[45] As technology became more complex, its development relied more and more on the overlap between different areas of expertise. Electrical engineers interacted with materials scientists and mechanical engineers on some days, and computer scientists and mathematicians on others. Government agencies became some of the most common brokers in this scene.

Already in the years immediately following the end of the war, government agencies were playing a key role in establishing common goals and resolving technical controversies

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[44] Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm 1870-1970* (New York: Penguin Books, 1989).

[45] Loet Leydesdorff and Henry Etzkowitz, 'Emergence of a Triple Helix of University-Industry-Government Relations', *Science and Public Policy*, 23.5 (1996), 279–86 <https://doi.org/10.1093/spp/23.5.279>; Henry Etzkowitz, 'Innovation in Innovation : The Triple Helix of University-Industry-Government Relations', *Social Science Information*, 42.3 (2003), 293–337.

around the development of any number of large-scale military technologies, from ICBMs and missile defense systems,[46] to fighter jets.[47] It was not only military laboratories that showed this new tendency. Governance structures themselves had become networked, so that policymaking depended on navigating a complex set of relationships in order to get anything done.[48] Organizational forms in the business world took a similar turn, as multinational companies and company partnerships blurred the lines between firms and the fundamental unit of the economy increasingly verged toward network organizations.[49] This has only become more common over time, with developmental states harnessing industry with central coordinating agencies[50] and policy around national innovation systems emphasizing the positive role governments play in coordinating and amplifying industrial R&D.[51]

One especially extreme form of government coordination is mission-based innovation, where government encourage the development of technology to address specific strategic

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[46] MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*; Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*.

[47] Law and Callon.

[48] R. A. W. Rhodes, *Understanding Governance: Policy Networks, Governance, Reflexivity, and Accountability* (Philadelphia: Open University Press, 1997).

[49] John F. Padgett and Walter W. Powell, *The Emergence of Organizations and Markets* (Princeton, N.J.: Princeton University Press, 2012); Walter W. Powell, 'Neither Market nor Hierarchy', *Research in Organizational Behavior*, 12 (1990), 295–336; Joel M Podolny and Karen L Page, 'Network Forms of Organization', 24 (1998), 57–76 <https://www.jstor.org/stable/223474>.

[50] Peter Evans; Chalmers A. Johnson, *MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925--1975* (Stanford: Stanford University Press, 1982); Block.

[51] Bengt Åke Lundvall, 'National Innovation Systems - Analytical Concept and Development Tool', *Industry and Innovation*, 14.1 (2007), 95–119 <https://doi.org/10.1080/13662710601130863>.

goals.[52] This was driving force behind the Manhattan Project and the Apollo missions, but also more recent efforts like Horizon Europe and the War on Cancer. By directing resources toward specific goals and playing the coordinator in joint R&D partnerships, government attempts to induce research to follow particular research trajectories. The historical record suggests that many of these efforts can be positive, though the outcomes are far worse when government takes too direct a role in picking and choosing between alternative technologies.[53]

Government power in a complex economy

The core argument in this dissertation is that the existing perspectives on government intervention oversimplify an otherwise complex economy.[54] I mentioned already that markets, when left to their own devices, suffer from a well-known failure to provide enough investment for R&D.[55]

Science is not without its shortcomings either. The impact of things like Galileo's observations of Jupiter or Einstein's theory of relativity suggested to philosophers of science like Kuhn and Feyerabend that the accumulation of knowledge in science was not

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[52] Mazzucato, 'Financing Innovation: Creative Destruction vs. Destructive Creation'; Thomas P. Hughes, *Rescuing Prometheus* (New York: Vintage Books, 2000); Nelson.

[53] Richard R. Nelson and Richard N. Langlois, 'Industrial Innovation Policy: Lessons from American History', *Science*, 219.4586 (1983), 814–18 <https://www.jstor.org/stable/1689818>.

[54] cf. David C. Mowery, Richard R. Nelson, and Ben R. Martin, 'Technology Policy and Global Warming: Why New Policy Models Are Needed (or Why Putting New Wine in Old Bottles Won't Work)', *Research Policy*, 39.8 (2010), 1011–23 <https://doi.org/10.1016/j.respol.2010.05.008>.

[55] Kenneth J. Arrow, 'Economic Welfare and the Allocation of Resources for Invention', in *The Rate and Direction of Inventive Activity: Economic and Social Factors* (Cambridge, MA: National Bureau of Economic Research, 1962), pp. 609–26 <http://www.nber.org/chapters/c2144>.

always steady and not always rational.[56] In the decades since, scientists have been shown to pick their research topics not just according to what would make the most progress, but according to scholarly trends,[57] their own existing knowledge and expertise,[58] and the available funding.[59] This all indicates just how risk-averse scientists can be when they choose topics for their research. It may be the right decision for a scientist's own career, but science would be better off if scientists took more risks with their research.[60] Just as significant is that scientists face a major glut of information with all the new research that gets published every year. This effectively makes the search space too large for science to explore, leading to a stale canon and an inefficient use of human capital.[61]

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[56] Kuhn, *Struct. Sci. Revolutions*; Paul Feyerabend, *Against Method* (London: New Left Books, 1975).

[57] Rzhetsky, Iossifov, and others.

[58] Jacob G. Foster, Andrey Rzhetsky, and James A. Evans, 'Tradition and Innovation in Scientists' Research Strategies', *American Sociological Review*, 80.5 (2015), 875–908 <https://doi.org/10.1177/0003122415601618>; Andrey Rzhetsky, Jacob G. Foster, and others, 'Choosing Experiments to Accelerate Collective Discovery', *Proceedings of the National Academy of Sciences of the United States of America*, 112.47 (2015), 14569–74 <https://doi.org/10.1073/pnas.1509757112>.

[59] Lixia Yao and others, 'Health ROI as a Measure of Misalignment of Biomedical Needs and Resources', *Nature Biotechnology*, 33.8 (2015), 807–11 <https://doi.org/10.1038/nbt.3276>; Laudel; Carlotta Perez, *Technological Revolutions and Financial Capital* (Cheltenham, U.K.: Edward Elgar Publishing, 2003).

[60] Thomas S. Kuhn, *The Essential Tension. Selected Studies in Scientific Tradition and Change* (Chicago: University of Chicago Press, 1979) <https://doi.org/10.2307/2504757>.

[61] D. R. Swanson, 'Fish Oil, Raynaud's Syndrome, and Undiscovered Public Knowledge.', *Perspectives in Biology and Medicine*, 30.1 (1986), 7–18 <https://doi.org/10.1353/pbm.1986.0087>; D. R. Swanson, 'Medical Literature as a Potential Source of New Knowledge', *Bulletin of the Medical Library Association*, 78.1 (1990), 29–37; Johan S.G. Chu and James A. Evans, 'Slowed Canonical Progress in Large Fields of Science', *Proceedings of the National Academy of Sciences of the United States of America*, 118.41 (2021), 1–5 <https://doi.org/10.1073/pnas.2021636118>.

Criticism of government intervention in science starts from a somewhat different perspective, one that holds government intervention in science and technology in comparison with market mechanisms themselves. In an important way this also marks the origins of the science of science. In the late 1930s, the chemist Michael Polanyi—who also happens to be the brother of Karl Polanyi, the equally well-known economist—attended a conference on the future of science where he was able to hear an address from Nikolai Bukharin,[62] close friend of Stalin's and one of the founding members of the Soviet Academy for Arts and Sciences. Polanyi reported being shocked by the apparent heavy-handed central planning of science by the Soviet state.[63] The experience seems to have inspired him to take a more active role in articulating an understanding of science that was more grounded in the free market, and to champion science policy that reflected that.

His concerns were not entirely misplaced. Trofim Lysenko's dubious theories of genetic inheritance—which are often blamed for the frequent famines and overall poor agricultural productivity in the early decades of the Soviet Union and communist China—had just recently been aggressively promoted by the state. This had gone so far that rival biologists who refused to adopt Lysenko's theories had been exiled, imprisoned, and even killed. Meanwhile, here was the Bukharin, the architect of science policy in the Soviet Union,

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[62] The talk was said to have occurred in 1935, but I have been unable to track that down. Bukharin gave a very similar speech in 1931, however. Curious readers can see N. I. Bukharin, 'Theory and Practice from the Standpoint of Dialectical Materialism', in *Science at the Cross Roads: Papers Presented to the International Congress of the History of Science and Technology* (London: Kniga Ltd., 1931), pp. 1–23.

[63] Michael Polanyi, *The Contempt of Freedom: The Russian Experiment and After* (London: Watts & Co., 1941), pp. 3–5.

explaining how dialectical materialism implied that research ought to align with state priorities.

Polanyi took a very different approach in his response. He suggested that when left alone, science naturally came to a sort of "spontaneous order" that sorted out good ideas from bad ones.[64] In this way it functioned like a market, with competition working as a selection mechanism for ideas. Indeed, Polanyi was a regular correspondent of the well-known economist and libertarian Friedrich Hayek. The similarity in how they spoke of science and markets is striking. Here, for instance, is Hayek explaining the marvel of market mechanisms:

> "The marvel is that in a case like that of a scarcity of one raw material, without an order being issued, without more than perhaps a handful of people knowing the cause, tens of thousands of people whose identity could not be ascertained by months of investigation, are made to use the material or its products more sparingly; i.e., they move in the right direction."[65]

The idea that science naturally veers toward the right answer is a powerful one. As a social process science and markets are assumed to work like an optimization process. Let me give an illustration to explain.

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[64] Michael Polanyi.

[65] F. A. Hayek, 'The Use of Knowledge in Society', *American Economic Review*, 35.4 (1945), 519–30 (p. 527) <https://www.jstor.org/stable/1809376>.

Suppose that human beings decided collectively that they needed to find the tallest mountain.[66] They know that there are mountain ranges all over the planet, and consequently that this is a deceptively difficult question to find an answer to. If one team of researchers sets out on an expedition to find the tallest mountain, how well they fare is going to depend on where they start looking. If they start by looking in the Rocky Mountains, it is bound to take a very long time until they realize that the right answer is in the Himalayas. The search depends on the landscape and on the starting point.[67]

Market mechanisms and the "spontaneous order" in science work by decentralizing the search process. Rather than sending out a single team, thousands upon thousands of expeditions set out to find the tallest peak. It may take one team a very long time to find the right answer, depending on where they begin their search, but each expedition will have its own reasons for searching for the right answer in one place or another. This decentralization is one of the main strengths of the search process, as it enables wider exploration of the landscape. With so many teams searching at the same time, it is virtually guaranteed that someone will find the right answer quickly and communicate it to everyone else. In fact, one way to understand the concerns around government

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[66] This metaphor draws heavily on research about 'recombinant search.' See Fleming; Fleming and Sorenson, 'Technology as a Complex Adaptive System: Evidence from Patent Data'; Lee Fleming and Olav Sorenson, 'Science as a Map in Technological Search', *Strategic Management Journal*, 25.8–9 (2004), 909–28 <https://doi.org/10.1002/smj.384>; Shahar Avin, 'Centralized Funding and Epistemic Exploration', *The British Journal for the Philosophy of Science*, 70.3 (2019), 629–56 <https://doi.org/10.1093/bjps/axx059>; Christopher Watts and Nigel Gilbert, 'Does Cumulative Advantage Affect Collective Learning in Science? An Agent-Based Simulation', *Scientometrics*, 89.1 (2011), 437–63 <https://doi.org/10.1007/s11192-011-0432-8>.

[67] This is comparable to the optimization problem in statistics. Even with techniques like gradient descent, where you start in the landscape affects how long it takes the model to arrive at its final estimate. In most landscapes the starting point even determines whether gradient descent finds the right answer or not.

intervention is that it may homogenize the various expeditions and allocate too much attention to specific parts of the landscape.

What I would like to argue is that over and above this risk, government intervention has a more direct influence on the search process in science—on its spontaneous order—by shaping the landscape itself. Almost as if the government made some mountains larger and some valleys deeper, government interventions in science and technology changes the possibility for innovation around certain technologies. New equipment certainly spurs scientific innovation in a general sense.[68] But certain kinds of equipment depend almost exclusively on the government for their deployment and may be especially prone to impacting future innovation.

Consider the high-risk investments governments are often expected to make toward infrastructure or large technical systems. These technologies provide crucial components for future innovations while also being something that markets were unlikely to deliver in the first place. Launching GPS satellites, for instance, did not disrupt market mechanisms or science's spontaneous order. But it did have a remarkable impact on research that depended on positioning and navigation. The same story can be told with respect to the way deep space research is only possible with enormous telescope installations on earth, or space telescopes in orbit. The new possibilities offered by technology lures researchers to new topics, much as research funding does. To the extent that governments can change

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[68] e.g. Landecker.

the potential for innovation by providing key technology, government interventions may leave a larger mark through its landscaping than through its disruption.

Another reason to suspect that government intervention has this second landscaping effect is that the diffusion of new ideas is not automatic and effortless. For an innovation to move from one place to another, some researcher needs to recognize the value it has in another domain and understand how it can be applied to a new use case. Hargadon and Sutton have suggested that there are only a small number of firms that can play this role, because it relies so much on straddling the boundary between markets.[69] This probably overstates the point since the movement of workers in and out of a company creates connections of its own. But in any case, recent work has suggested that governments play a role in technology brokerage as well.[70] In introducing technology to new areas of scientific research, governments can open all sorts of new avenues for inquiry, all without disrupting the existing search processes in science.

Empirical expectations

I make three main claims in this dissertation.

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[69] Andrew Hargadon and Robert I. Sutton, 'Technology Brokering and Innovation in a Product Development Firm', *Administrative Science Quarterly*, 41.4 (1997), 685–718 <https://www.jstor.org/stable/2393655>.

[70] Steven Samford, 'Networks, Brokerage, and State-Led Technology Diffusion in Small Industry', *American Journal of Sociology*, 122.5 (2017), 1339–70 <https://doi.org/10.1086/690454>; Marian Negoita and Fred Block, 'Networks and Public Policies in the Global South: The Chilean Case and the Future of the Developmental Network State', *Studies in Comparative International Development*, 47.1 (2012), 1–22 <https://doi.org/10.1007/s12116-012-9097-4>; Jorg Janischweski, Mikael P Henzler, and W Kahlenborn, *The Export of Second-Hand Goods and the Transfer of Technology* (Berlin, 2003).

(1) Governments have a major impact on inducing researchers in science and industry to study specific topics.

This is the commonplace argument around government intervention and its disruption of market mechanisms. At the bare minimum, researchers will only spend their energy studying a topic if they know there is an audience or a market for that work. Dosi has referred to this as first-order selection.[71]

Government funding of research is the most straightforward mechanism that leads to this selective effect. While it is far from the only thing that scientists consider when they are deciding between research projects, scientists have been shown to strategically choose their projects in response to funding trends.[72] Government has a similar effect when they offer support to markets, for instance by offering subsidies to make a niche or emerging market profitable for businesses, or when the government is the only potential buyer for a technology, as it tends to be with military goods like fighter jets or missiles.[73]

The final two claims have to do with government's ability to shape the landscape for scientific research. That is, in contrast to the first claim, which focuses on how governments disrupt market mechanisms or scientific spontaneous order, the following two claims

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[71] Dosi.

[72] Laudel.

[73] David C. Mowery, 'Military R&D and Innovation', in *Handbook of the Economics of Innovation* (Elsevier B.V., 2010), II, 1219–56 <https://doi.org/10.1016/S0169-7218(10)02013-7>; Francesco Decarolis and others, 'Buyers' Role in Innovation Procurement: Evidence from US Military R&D Contracts', *Journal of Economics and Management Strategy*, 2021 <https://doi.org/10.1111/jems.12430>.

relate to how governments impact research without disrupting those mechanisms. I focus on the government's role in the diffusion of knowledge. Thus, the second claim:

(2) Governments affect innovation by serving as a technology broker, helping to import ideas and technologies from one field of research to another. In so doing, governments create new possibilities for research.

This is meant to capture the fact that government transforms the research landscape, along with the main mechanism that produces that effect.

Now, governments are not the only actor that can serve as a technology broker. At one point in the history related in my dissertation, it will become clear that the diffusion of knowledge also serves to mitigate many of the negative consequences that stem from the first-order selection of research topics that was the subject of the first claim. So just as diffusion empowers government to spur innovation, it also sets some limits on how much bad the government can do in the worst-case scenario for government intervention.

Finally, the second claim needs to be tempered, because not all technology brokerage is helpful. The third claim frames it like this:

(3) When governments successfully introduce new technology, the success of any new lines of research will depend on how much friction they add to existing knowledge and workflows in a field.

The idea that diffusion does not necessarily lead to the adoption of an innovation is an old one and a common one.[74] But over and above this, case studies on scientific discovery have shown time and again that new ideas often disrupt the existing relationships between contributors, data collection, statistical models, and technology.[75] It takes considerable effort to make scientific research run efficiently, and its accomplishment helps turn scientific and technical work into the famous "black box" of science studies, where the underlying work is made invisible thanks to the way it has become taken for granted.[76]

Some innovations can be easily slotted in to established practices without disrupting what is taken for granted—that is, without adding any friction. But because governments are incentivizing research from the outside, they run a higher risk of disrupting accepted practice, or simply introducing ideas that do not fit with the larger field of study. In this way, even if governments are entirely successful in growing the interest around specific research topics, scientists may spend the bulk of their time trying to sort out the friction that was introduced rather than producing innovative work.

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[74] e.g. Bryce Ryan and Neal C Gross, 'Acceptance and Diffusion of Hybrid Corn Seed in Two Iowa Communities', *Agricultural Experiment Station - Iowa State College of Agriculture and Mechanic Arts*, 372.372 (1943), 663–705 <https://doi.org/citeulike-article-id:1288385>; Abhijit Banerjee and others, 'The Diffusion of Microfinance', *Science*, 341.1236498 (2013), 1–7 <https://doi.org/10.1126/science.1236498>.

[75] Emmanuel Didier, *En Quoi Consiste l'Amérique?: Les Statistiques, Le New Deal et La Démocratie* (Paris: La Découverte, 2009); Law and Callon; Latour, *The Pasteurization of France*; Alain Desrosières, *Pour Une Sociologie Historique de La Quantification: L'Argument Statistique I* (Paris: Presses des Mines, 2008); Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*.

[76] Pinch and Bijker; Bruno Latour, *Pandora's Hope: Essays on the Reality of Science Studies* (Cambridge, MA: Harvard University Press, 1999); c.f. Langdon Winner, 'Upon Opening the Black Box and Finding It Empty: Social Constructivism and the Philosophy of Technology', *Science, Technology & Human Values*, 18.3 (1993), 362–78 <https://doi.org/10.1177/016224399301800306>.

Government investment and coordination is a powerful device for impacting the accumulation of knowledge and the evolution of technology. But none of government's powers curtail the brokerage that already exists in the economy, nor do they simplify the work of incorporating an innovation into a new domain. Research needs to take a wider lens on how governments impact innovation in the long run, and how far its influence goes before it is diluted by the complexities of science and the economy. This is where I turn my attention now.

A note on terminology

It should be clear by now that I will be writing a lot about government. But as social scientists have pointed out for decades, governments are complex things, held together despite competition between agencies and jurisdictions.[77] For the most part, when I say "government" I will be referring to the federal government in the United States. Inter-agency competition is not a major part of the story I am going to tell, so I typically also attribute to the actions of federal agencies to "the government" as well, even though this is not strictly accurate. Nevertheless, there are a few occasions where it is important to distinguish between agencies, or between federal and state governments, and in one situation, between the governments of different countries. I have done my best to be clear about my referents in these cases.

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[77] Joel S Migdal, *State in Society: Studying How States and Societies Transform and Constitute One Another* (New York: Cambridge University Press, 2001).

Methodology

The question at the heart of this dissertation is a historical one: how does deliberate government action around innovation affect the long-term accumulation of knowledge and the evolution of technology. I try to provide an answer using the historical comparison of two sets of technology, one around weather forecasting and the other around in-vehicle road navigation. Both cases are set in the period from the Second World War to the mid-1970s.

The historical construction of government impact

There are strategic reasons for my focus on this period. In the first place, it has captured the imagination of scholars, policymakers, and the public, alike. This alone makes it worthwhile to study, if only for the sake of better understanding one of the standard reference points for people seeking to understand how governments affect science and technology. But there is another reason, as well. Namely, nearly everything aligned in this era to give the US government every advantage in affecting the direction of research. My research design takes advantage of this to explore what the upper limits of government power look like around the issue of innovation.

Why does the United States in the mid-20th century stand as an extreme case? Many scholars have correctly observed that the Cold War environment may well have provided extra incentive for the state to use a heavy hand in guiding science.[78] Science, it should be

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[78] Block; Desrosières, chap. 3; Foray, Mowery, and Nelson; Mowery, 'National Security and National Innovation Systems'.

said, has always been closely connected to the state. The ecological sciences and the human sciences flourished under colonialism. Merchant and military vessels brought back specimens from all over the planet, testifying to the sheer diversity of nature.[79] Darwin was sailing with the British Navy when he visited the Galapagos Islands and developed his ideas around evolution. Scientific racism developed in conjunction with the Transatlantic slave trade. The same close relationship exists for fields like sociology.[80] The state has always exerted a certain gravitational force on scientific research, and this was certainly equally true during the Cold War, with enormous amounts of resources being committed to the arms race between the United States and the Soviet Union.

But for a historical social scientist this is not the only, and maybe not even the most telling feature of the moment in time immediately following the Second World War. Rather, what marks it out is threefold. In the first place, science as an institution takes on an almost entirely new character in the post-war period. When I say "science" I very consciously include more than just the work that happens at universities. From the Second World War through to the mid-1970s science was just as much housed within large government and industrial laboratories as it was in the academy.[81] The period here was punctuated on the

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[79] Harold J Cook, *Matters of Exchange: Commerce, Medicine, and Science in the Dutch Golden Age* (New Haven: Yale University Press, 2007); Brett M. Bennett and Joseph M. Hodge, *Science and Empire: Knowledge and Networks of Science Across the British Empire, 1800-1970*, *Science and Empire* (New York: Palgrave MacMillan, 2011).

[80] George Steinmetz, *Sociology & Empire: The Imperial Entanglements of a Discipline* (Durham: Duke University Press, 2013).

[81] Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm 1870-1970*; Jacob Schmookler, 'Inventors Past and Present', *The Review of Economics and Statistics*, 39.3 (1957), 321–33 <https://www.jstor.org/stable/1926048>; Peter J. Westwick, *The National Labs: Science in an American System, 1947-1974* (Cambridge, MA: Harvard University Press, 2003).

one end by the large industrial laboratories like those at Bell and DuPont eclipsing the role of independent inventors in producing innovation, and on the other end by the declining importance of industrial R&D in basic science as businesses increasingly sought to pursue applied research. This period of time that so frequently gets valorized in the discussion around government encapsulates the lifetime of a distinctive division of labor for innovation.

The second thing that makes this an odd historical comparison point is that the post-WW2 period brought with it the revolutionary impact of computing technology. As scholars have noted for decades now, the consistent (and rapid) increase in computational power over the 20th and 21st centuries has continually renewed scientific research, helping to amplify the skills and accumulated knowledge of scientists.[82] But in the years immediately following the war the impact of computation was more categorical. Scientists in the 1950s did not just have more computational power, they had computational power orders of magnitude beyond what previously existed through the applied effort of human beings. Correspondingly, this meant that scientific knowledge which had long been merely theoretical was suddenly applicable for more practical research.

Consider the example of Lewis Fry Richardson's attempt to compute a weather forecast by hand in 1922. The process was so time-intensive that he mused on what it would take to deliver next-day weather forecasts, finally concluding that it would require over 64,000

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[82] Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*; James Evans and Andrey Rzhetsky, 'Machine Science.', *Science*, 329.5990 (2010), 399–400 <https://doi.org/10.1126/science.1189416>; David Lazer and others, 'Life in the Network: The Coming Age of Computational Social Science', *Science*, 323.5915 (2009), 721–23 <https://doi.org/10.1126/science.1167742.Life>.

people with strong mathematical abilities, their work carefully orchestrated in a massive auditorium.[83] Just a little over two decades later, the world's first programmable and all-purpose computer was built at the University of Pennsylvania. In 1950 that computer completed the computation of a next-day weather forecast in just under 24 hours.

It was not just meteorology that benefited from computers. They upended science in both universities and industrial labs. The level of impact that computer technology had on innovation in this period is rivaled historically only by the transformations that stemmed from the steam engine. At the same time, early computers were so large and expensive that only the largest corporations, or government-sponsored laboratories could afford to house one. As a result, the large-scale government interventions that are celebrated from this period seem likely to be considerable historical outliers.

There is one final aspect of the United States in the mid-20th century makes it a questionable comparison point for the debate around government intervention and innovation. The end of the Second World War brought an unprecedented influx of human capital to the United States, many of whom fled during the war, while still others were recruited through programs like Operation Paperclip. A significant number of these scientists ended up working within government labs on national priorities. It was German rocket scientist Wernher von Braun, after all, who designed the launch vehicle for the Apollo missions along with his team. Governments around the world, whether after WW2 or today, cannot reasonably plan on that same rush of scientific expertise.

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[83] Lewis Fry Richardson, *Weather Prediction by Numerical Process* (Cambridge, U.K.: Cambridge University Press, 1922).

The circumstances at work in mid-20th century were unusual enough as to make it unlikely that other countries could match the sway that the United Stated held over science and technology. While it is not a representative case, but an extreme one, this does make it possible to establish some expectations about the upper limits of how much control states can have on the accumulation of knowledge and the evolution of technology.

Comparison at the extreme

The logic of inquiry in this dissertation is organized around a comparison at the extreme. As I just mentioned, the national context in the period that the analysis covers is itself extreme in a historical sense. But within this context I also compare two cases that highlight the power of governments to set agendas in R&D.

One case, weather forecasting, experienced an extreme level of government intervention for decades, leaving the appearance of a heavy-handed state directing the accumulation of knowledge toward its own priorities. The second case, in-vehicle road navigation, draws an interesting contrast in that government originally provided material support for the research trajectory in this domain, before eventually deciding to withdraw that support. The effect of this withdrawal makes it possible to isolate some of the impact that deliberate government action had on R&D in this period. My research design thus combines extreme case analysis in the periodization with a more traditional comparison therein, highlighting the power of government at time when government power around innovation was at or near its peak.

As with any historical study, the two sets of technology eventually change enough to make any strict comparison unreasonable. This happens precisely because of the differences in how government chose to sponsor (or not sponsor) R&D in each case. That said, I continue to follow the history of each case to see the long-term consequences of these decisions. What happened to R&D in weather forecasting as the government continued to make extravagant investments into new technology? What happened for in-vehicle road navigation technology after the government withdrew from the domain? By continuing to trace the history of each case, I am able to identify some limiting factors to the government impact that was identified through the original comparison.

Data

The bulk of the research presented here is based on archival materials from across the United States. I benefitted immensely from the National Archives in College Park, and in Washington D.C., as well as the Presidential Libraries for Bill Clinton, Ronald Reagan, and Richard Nixon. The internal libraries for a number of US government agencies were also helpful. I am especially indebted to those at the National Atmospheric and Oceanic Administration, the Department of Transportation, and the Bureau of the Census. I also draw on materials gathered via Freedom of Information Act Requests at the Air Force and the Bureau of the Census.

Private sector archives were also extremely helpful in this project. I rely heavily on materials from the General Motors Research Laboratory archives, the RAND archives, Newberry Library's Rand McNally and Gousha collections, and the archives of the World Meteorological Organization.

In addition to these archival materials, I have also consulted a wide range of technical reports and patents on the relevant technology. US patent data before 1976 does not follow any consistent reporting standard, making quantitative analyses difficult for the period under consideration, though I do provide some simple distributional information as part of Chapter 4. It goes without saying that I am also the beneficiary of the work done by many historians before me. I am grateful to be building on their insights.

Outline of the argument

I start in Chapter 2 by asking how the differences in government support for weather forecasting and smart highway research affected whether the technology was deployed and whether research into the technology continued over time. The historical evidence indicates that government support played the decisive role for both research trajectories. R&D around weather forecasting was reliably provided with ample resources to bring new technologies like computers, weather balloons, radar, and satellites to bear on the problem of providing operational forecasts. This stands in sharp contrast to smart highway research, which never came to fruition. While the government was eager to support R&D in this area throughout the 1950s and 1960s, allowing knowledge and technological innovations to accumulate in the area, that support was withdrawn in 1971 and R&D was shut down across industrial and government laboratories. The comparison in that chapter draws out fresh evidence in favor of Polanyi's longstanding complaint that says government intervention in science picks and chooses research topics.

Chapter 3 prods at the limitations that governments have in setting research agendas by investigating how weather forecasting researchers responded to the new technology that the government was providing them with. Specifically, why was it that some technologies, like radar and satellites for instance, faced so many challenges in getting weather forecasters to make use of them. It took repeated pressure from the federal government for R&D to gain traction around these technologies. I treat this as an issue of technology brokerage and show that while the government provided material support and transferred new technology into the weather forecasting domain, radar and satellite data were largely incommensurable with the predominant practices in the field. Even when R&D gained momentum around the new technologies, it was almost entirely aimed at finding ways to render the data commensurate with existing approaches. Radar and satellite technology would eventually have a major impact on weather forecasting, but not until weather forecasting had a major impact on radar and satellites. The findings provide strong evidence that the government shaped weather forecasting more through its landscaping powers than by disrupting the spontaneous order in science.

Where Chapter 3 considered the consequences of the government setting a research agenda in weather forecasting, Chapter 4 looks at what came of the government's shutting down of the research agenda for smart highways. As it turns out, many of the ideas around smart highways were picked up in other countries and even by related industries, like agriculture and warehousing. Governments may have decisive power in the markets they dominate—like the one around smart highways—but the diffusion of innovations means that governments are also very limited in their ability to impact overall knowledge accumulation. Chapter 4 closes with the story of how GPS navigation was developed, and the unwittingly innovative role that the US government played in that story. Just as government did not prevent the spread of the technology around smart highways, so too did it develop key technologies that made modern GPS navigation possible without intending to. In fact, the government resisted its own innovations, and ultimately failed to do so.

Chapter 5 is the conclusion to this dissertation. I begin by summing up the overall argument and its implications. With two of the most extreme cases, from the most extreme period for US intervention around innovation, government appears decisive in setting research agendas. But simultaneously that power is limited by the ability of researchers to incorporate into their normal practices what government pushes onto them, and limited in scope to its own economy and to the industries it chose to intervene in. What's more, the larger impact of government intervention appears to have to have come not by disrupting the search mechanisms in science, but by changing the research landscape itself through the introduction of new technology.

Seen from the perspective of how knowledge accumulates, governments matter. The now-global system for weather forecasting remains one of the most impressive feats of the 20th century and it would have almost certainly been impossible without the heavy-handed intervention of government. Similarly, the decision to withdraw support for smart highways may have cost a substantial amount of compounded economic growth, even as the government's sponsorship of GPS technology transformed the economy at the turn of the millennium. But government is not strong enough to force R&D in radically new directions, nor is its power so wide-reaching that it can single-handedly relegate ideas to history's garbage bin.

Chapter 2:

Adopted and abandoned by the government

Introduction

I have set out in this dissertation to probe the upper limits of government power in affecting the long-term accumulation of knowledge and evolution of technology. Building on the metaphor of expeditions setting out to find the tallest mountain, I suggested that governments have two ways to shape research. They can direct research toward specific parts of the scientific landscape and they can change the landscape itself by introducing new technologies, as if they were making some mountains taller and some valleys deeper. This chapter does double-duty in dealing with the first of these two mechanisms and introducing the two focal cases for this dissertation.

The motivating question here is how much influence the government has in attracting researchers to a given topic or pushing them away. This gets back to the basic complaint about government intervention in science, one that goes all the way back to Michael Polanyi: if science has a "spontaneous order" that leads scientists toward the most productive research topics, as many have suggested, then government intervention risks disrupting that.[84] As I show here, there is good evidence that the government does in fact

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[84] Michael Polanyi; see also Nelson and Langlois; Nelson.

play a decisive role in shifting research to and away from specific technologies. This is because some technologies—in particular, complex and expensive technologies[85]—depend on the government to adopt them. Research into these technologies only begins when the government shows interest as a buyer and it can end just as quickly when the government withdraws its apparent interest.

Giovanni Dosi called this the "first-order selection" of research trajectories, since market interest (in a broad sense) works almost like a pre-requisite for scientific research.[86] If this thinking is right, there should be a tight relationship between the government sponsorship of a given technology—shorthand for how much interest the government shows in the technology, and how active it is in coordinating research around it—and the outcome of whether the technology is adopted or abandoned.

The evidence in my two cases here is supportive of this view, giving the impression of a fairly powerful state. Not only did the US government decide which of the technologies it would deploy, it also dictated the direction that research would take in both areas. The main limiting factors to this argument are the topic of Chapters 3 and 4.

As the history here shows, the events around weather forecasting and in-vehicle road navigation give leverage on the matter of the government's ability to direct research toward one topic or another. Until 1971, when Congress decided to withdraw its funding for in-vehicle road navigation, the US government was heavily involved in developing new

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[85] Mazzucato, 'Financing Innovation: Creative Destruction vs. Destructive Creation'; Boyan Jovanovic and Peter L Rousseau, 'General Purpose Technologies', *NBER Working Paper*, 11093 (2005) <http://www.nber.org/papers/w11093>; Block.

[86] Dosi.

technologies in each case. In fact, there are good indications that this research would never have started if it were not for the interest government was signaling around them. Just as tellingly, research into in-vehicle road navigation conspicuously stopped almost immediately after Congress' decision, something that delayed the availability of in-vehicle road navigation for 30 years. Had the government continued to support it, drivers may have had Google Maps—its equivalent, anyway—almost thirty years early.

Table 1 summarizes the evidence presented below on a case-by-case basis. Table 2, toward the end of the chapter, provides the same information on a technology-by-technology basis. The remainder of this chapter is organized around the two main cases. I explain the basic workings of weather forecasting and in-vehicle road navigation and do my best to describe how each new technology fits into those projects. The brief historical narrative around each one highlights how government sponsorship, or lack thereof, led to the success (or otherwise) of each technology.

	Weather Forecasting	*In-Vehicle Road Navigation*
Cost of necessary infrastructure	High	High
Expected return on investment	High	High
Technology benefits military	Minimally	Minimally
Government laboratories involved in R&D	Directly	Directly
Government is the intended provider	Yes	Yes
Government support for and interest in the technology	Consistent	Sporadic
Systems adopted or abandoned	**Adopted**	**Abandoned**

Table 1: Government support explains which technological systems were built*. Cost of the necessary infrastructure was a requirement for case selection, and expected return on investment reflects estimates from the period made by the Congressional Budget Office. Technology benefits military is an estimate, as this varies from technology to technology within weather forecasting (see Table 2 for more details). Government laboratories involved in R&D is drawn from the historical record, as is whether government is the intended provider and the consistency of government support and interest. Whether systems were adopted or abandoned is not a reflection of whether R&D was conducted, or how much progress that R&D made, but simply whether the technologies were put to use.*

Weather Forecasting

Making sense of the US government's role in fostering weather forecasting research requires that I step back to the turn of the 20th century. Governments around the world had gotten involved in collecting meteorological data in the name of military interests far earlier, but around this time an entirely new approach to weather forecasting took hold in the scientific imagination—numerical weather prediction. As I explain below, despite its potential, numerical weather forecasting faced two fundamental problems: virtually no one was collecting the right kind of data, and there was no practical way to finish the necessary calculations fast enough to issue weather forecasts.

Advances in technology solved both problems. The necessary data for numerical weather prediction was being collected systematically already by 1910. Meanwhile, computers were helping to overcome the challenge of quickly running calculations by the mid-1950s.

The first two subsections below give the necessary history for the early days of numerical weather prediction research, highlighting the importance of the government in moving it forward. This support continued through the middle of the 20th century, with technology like radar and satellites. This is addressed in the third and final subsection, though much of the history around radar and satellites is dealt with in Chapter 3.

Welcome to the forecast factory

Weather forecasting before the 20th century was an extremely local affair. This is not to say that there were not national or global experts on meteorology, only that the practice of predicting the weather two or three days out was a matter of applying the historical experience of a local area to make a reasonable guess about what would happen tomorrow.

Almanacs, for instance, were assembled for this reason. If you wanted to know what to expect in Boston over the winter, consult the almanac! It would tell you what Boston was like in the winter last year, and the year before, and the year before that. Here is how Cleveland Abbe, the foundational meteorologist in the United States, explained it:

> “At the present time, by the help of the daily weather map, the official weather forecasters of this country, and indeed of every civilized nation on the globe, publish forecasts, in detail, of approaching weather changes, and especially storms, for one and two, or possibly occasionally three days in advance. These predictions all relate to comparatively minute details for regions that have been charted and studied daily for many years. They merely represent the direct teachings of experience; they are generalizations based upon observations but into which physical theories have as yet entered in only a superficial manner if at all. They are, therefore, quite elementary in character as compared with the predictions published by astronomers, based on the laws of gravitation and inertia, or the predictions sometimes offered by chemists, based on the laws that are being worked out by these investigators.”[87]

Things started to change around the turn of the century when a few meteorologists worked on applying the principles of hydrodynamics and thermodynamics to the problem of the atmosphere. Abbe was among these few, explaining already in 1901 how this sort of

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[87] Cleveland Abbe, ‘The Physical Basis of Long-Range Weather Forecasts’, *Monthly Weather Review*, 1 (1901), 552–61 (p. 552).

approach could work.[88] It was Vilhelm Bjerknes who took the decisive step forward in 1904, identifying seven fundamental equations, derived from the Navier-Stokes equations, that would be necessary for any numerical weather prediction in the future.[89]

At the time there were two main obstacles to this approach. The first seems rather obvious upon inspection: there was simply not enough data from up in the atmosphere. Most of what matters for meteorology happens well above the surface of the earth. But at the beginning of the 20th century, human beings were still largely land bound. Aeronauts could explore the sky in balloons, but the airplane was still just novelty in Kitty Hawk. Abbe again:

> "One might have hoped that long continued records from mountain tops, and the numerous balloon ascensions of the last century, might have given us some basis for conclusions as to the conditions prevailing a few miles above sea level. But the more careful recent work with self-recording apparatus, and especially that with the so-called sounding balloons, has shown that at least in Europe, conditions prevail at great heights that were wholly unexpected."[90]

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[88] Abbe.

[89] Vilhelm Bjerknes, 'Das Problem Der Wettervorhersage, Betrachtet Vom Standpunkte Der Mechanic Und Der Physik', *Meteorolgische Zeitschrift*, 1904, 1–7; see also Peter Lynch, 'The Origins of Computer Weather Prediction and Climate Modeling', *Journal of Computational Physics*, 227.7 (2008), 3431–44 <https://doi.org/10.1016/j.jcp.2007.02.034>; Robert Marc Friedman, *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology* (Ithaca: Cornell University Press, 1993).

[90] Abbe, p. 559.

These “so-called” sounding balloons would eventually become the main data collection device for the upper atmosphere. It continues to be so even as of this writing. I will get back to balloons in a moment.

The second obstacle was just as substantial. As it turns out, it is very labor intensive to compute the solutions to Bjerknes’ seven equations. One enterprising mathematician in Great Britain, Lewis Fry Richardson, tried anyway.[91] His experience is instructive.

Richardson took the best dataset available to him at the time (sometime in the late 1910s)—one assembled, incidentally by Bjerknes—and created a grid over central Europe, using data from the 20th of May 1910 at 7AM UTC. Even more than a decade after Abbe and Bjerknes’ initial work, Richardson was still plagued by a lack of data in the upper atmosphere. In fact, only one balloon launched on that morning reached into the highest layer of Richardson’s model, and that balloon was launched in England, far from his chosen location in central Europe.[92]

The goal was to make a prediction of what the pressure and wind would be at the different points in his grid six hours after his starting point at 7AM. Richardson filled 23 Computer Forms in completing his forecast, each one something like a spreadsheet. He completed hundreds of computations by hand, many of which were far from trivial. The work was grueling: “It took me the best part of six weeks to draw up the computing forms and to

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[91] Richardson.

[92] see Peter Lynch, *The Emergence of Numerical Weather Prediction: Richardson’s Dream* (Cambridge, U.K.: Cambridge University Press, 2006), p. 107.

work out the new distribution in two vertical columns for the first time. My office was a heap of hay in a cold rest billet."[93]

Still, he believed that with enough skilled workers it should be possible for the math to at least keep up with weather. Some back of the envelope calculations led him to estimate that it would take about 64,000 people working around the clock to complete the necessary computations for the entire planet. He called his vision the "forecast factory," and went so far as to suggest that the workers could fill a theater. Its walls would be painted to represent the different regions of the world, and the workers beneath each painting would be set to working through the math for the designated region. Just as an orchestra has its conductor, so too did the forecast factory have its own "man in charge," standing at a podium in the center of the room, coordinating all the workers around him.[94]

This was the insurmountable challenge that faced weather forecasting in the early 20th century. But the US government, as was the case with many governments around the world, nevertheless invested large amounts of financial and human resources into pursuing the latest in weather forecasting. It had been invested heavily since the middle of the 19th century, when first, the potential for using weather forecasts for military advantage gained currency among the Civil War's military strategists, and when second, a series of extreme

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[93] Richardson, p. 219.

[94] I find Richardson's description of the "man in charge" to be very funny: "From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand." p. 219.

storms wrecked the Great Lakes region. In 1870 the US established the Weather Bureau—naming Abbe as the chief meteorologist—and placed it under the management of the military, believing that the need for quality weather information was high enough that it ought to be collected by the institution with the most administrative discipline and know-how. It was transferred to the Department of Agriculture in 1890.

The Weather Bureau acknowledged as early as 1895 that upper atmospheric data was going to be crucial for the future of weather forecasting but noted that the technology simply was not far enough along yet:

> “The difficult is to devise appliances, which, while captive, will carry automatically recording instruments to the proper elevation under all conditions of wind velocity and variable direction; but the obstacles do not seem to be formidable, and it is believed that they can be successfully overcome. (. . .) These appliances, however, have yet to be devised, and the contemplated system is consequently still in embryo."[95]

Things moved quickly, and in almost no time at all the US government was investing heavily in collecting the necessary data. By 1897 the Weather Bureau was experimenting with meteorographs—an automated instrument for recording meteorological measurements—affixed to kites "with the hope of ultimately being able to construct a daily synoptic weather chart from simultaneous readings taken in free air at an altitude of not

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[95] Willis L. Moore, *Report of the Chief of the Weather Bureau for 1895* (Washington: Government Printing Office, 1895), p. 92.

less than one mile above the earth."[96] As it turns out, the kites didn’t consistently reach the proper altitudes, so the institution began testing unmanned balloons to lift the meteorographs to the proper height in 1903.[97] A series of technical challenges delayed their widescale adoption, but the Weather Bureau officially began to switch its kite network over to a balloon-based "rawinsonde" system in 1937.[98] In the meantime, the Weather Bureau created a small network of airports partners to collect data by airplane,[99] a practice that continues to this day with commercial airliners.[100]

The advent of numerical weather prediction and the upper-air network ushered in a new era in the technical system around weather forecasting. Hundreds of professional weather stations were established under the purview of the Weather Bureau to collect atmospheric data, over and above the ground-level stations that already existed. At each one of these upper-air stations, balloons are released into the sky at regular intervals throughout the day with meteorological equipment to collect data on the state of the atmosphere within that vertical column on the map. This was the Weather Bureau's solution to the requirements of numerical weather prediction.

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[96] Willis L. Moore, *Report of the Chief of the Weather Bureau for 1897* (Washington: Government Printing Office, 1897), p. 26.

[97] Willis L. Moore, *Report of the Chief of the Weather Bureau for 1903* (Washington: Government Printing Office, 1903), p. 33.

[98] Willis Ray Gregg, *Report of the Chief of the Weather Bureau, 1937* (Washington: U.S. Government Printing Office, 1937), p. 5.

[99] C.F. Marvin, *Report of the Chief of the Weather Bureau* (Washington: Government Printing Office, 1925).

[100] The downside to this approach is that airplane meteorological data is essentially convenience data. They are not guaranteed to be arrayed in a way in space or over the course of the day that is amenable to numerical weather prediction.

The recognition that weather patterns are produced in the sky helped to fundamentally shift attention upward from the ground level. It also provided a large push toward the professionalization of the data collection operation in meteorology. Kites, balloons, and the theodolites that were used to track them, all require a fair amount of training and experience to use correctly, making it important to create a paid staff for the new upper-air stations rather than relying on volunteers.[101] The US government took the lead in establishing departments for meteorology in universities across the country and employing their graduates to staff forecasting offices and data collection stations.

When the Second World War broke out the Weather Bureau had already largely overcome the paucity of data that plagued early work on numerical weather prediction. Even with the rapid growth in the number of meteorologists, though, the US was not close being able to make Richardson's forecast factory a reality. But it was not far off—human computers just needed to be replaced with digital ones.

ENIAC, the weather, and the grid

As with many areas of science, the Second World War marks a decisive turning point for weather forecasting. Doppler radar was discovered during the London Blitz by radar operators. The emerging Cold War power structures motivated the development of satellite technology that offered an entirely new strategy for meteorological data collection. Put these aside for a moment, the next section addresses these developments.

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[101] Kristine C. Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (Cambridge, Massachusetts: MIT Press, 2008), chap. 3.

More important was the development of computers. The historical connection between computer technology and meteorology runs deep. It has long been a mutually beneficial relationship. Meteorology obviously gets to take advantage of growing computing power to deploy more and more powerful models. But computer technology also benefits from the ambition of meteorology. Whenever a computer scientist needs to test the limits of their system, there is always a weather model that can push it to the brink.

The first computer was developed as an offshoot of the Manhattan Project at the Institute for Advanced Study.[102] The ENIAC, short for the Electronic Numerical Integrator and Computer, was finished in 1945. In what seems to have been a coincidence, Francis Reichelderfer, the Chief of the Weather Bureau at the time, stumbled across the project while he was visiting Princeton to tour RCA's laboratory there.[103] Reichelderfer began immediately to encourage the ENIAC team to test out their new machine on a weather forecast. If a digital computer could really do the work of a skilled mathematician in just a fraction of the time, it had a chance to make even Richardson's imaginary forecast factory obsolete.

Money was secured for this work through a partnership that the Weather Bureau established with the Office of Naval Research, and a team made of meteorologists, mathematicians, and computer scientists set about crafting a weather model that could be run on ENIAC. The main limiting factor was the computer's memory capacity.[104] It was only

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[102] George Dyson, *Turing's Cathedral: The Origins of the Digital Universe* (New York: Vintage Books, 2012).

[103] Harper, chap. 4.

[104] J. G. Charney, R. Fjortoft, and J. Von Neumann, 'Numerical Integration of the Barotropic Vorticity Equation', *Tellus*, 2.4 (1950), 237–54 <https://doi.org/10.3402/tellusa.v2i4.8607>.

enough to store data and estimates for a 15x18 grid, which led the team to space the grid points by 736km. Nonetheless, the results were promising. The model was able to accurately predict the movement and growth of notable weather patterns for January 5, 30, and 31, as well as February 13, 1949, but many of the other details were woefully wrong, something the researchers attributed to the large grid sizes that ENIAC's memory limitations forced them to adopt.[105]

True to this experience, limits in computer memory and computational power became central factors in the development of weather forecasting over the next several decades. This meant that for much of the 20th century, the main theoretical advances around weather modeling came in countries that had access to state-of-the-art computers, and more specifically at institutions that had the same.[106] In the US this meant that three groups were responsible for the main innovations: the Geophysical Fluid Dynamics Laboratory at the Weather Bureau, the UCLA Department of Meteorology, and the National Center for Atmospheric Research, which was funded almost in its entirety by the federal government's National Science Foundation.

The development of atmospheric models over this period has been covered extensively by other scholars.[107] I will avoid re-treading that ground but interested readers can consult

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[105] Charney, Fjortoft, and Neumann, p. 247.

[106] For an interesting exception to this rule, see Vladimir Jankovic, 'Choosing the Right Axis : An Institutional History of the Belgrade Eta Forecast Model', in *Proceedings of the International Commission on History of Meteorology*, 2004, I, 92–98.

[107] Paul N. Edwards, 'A Brief History of Atmospheric General Circulation Modeling', *General Circulation Model Development, Past, Present and Future: The Proceedings of a Symposium in Honor of Akio Arakawa.*, 2000, 67–90 <https://doi.org/10.1016/S0074-6142(00)80050-9>; Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: MIT Press, 2010); Lynch, 'The Origins of Computer Weather Prediction and Climate Modeling'; Amy Dahan-Dalmedico, 'History and Epistemology of

the works cited in the footnote. However, there is something instructive about the pattern of improvements in weather modeling that emerged over time, as it underscores the fundamental limitations that computers placed on the research.

What changes consistently is that that the number of barometric levels included in weather model increases from model to model, while the grid size gets smaller (i.e., increasing the number of grid points).[108] The model run on ENIAC, as explained above, was limited to just one level. By 1956, when the US Weather Bureau began issuing daily weather forecasts using numerical weather prediction, its models had already advanced to a two-level model, and by 1959 it was experimenting with nine-level models. The interaction between computing advances and grid size is more easily seen in the UCLA models, which stuck with two-level models all the way through the 1960s. Instead of capitalizing on better computers by increasing the number of barometric levels in their model, they shrunk the grid size. The first-generation of models, circa roughly 1963, had a grid sized 7° of latitude by 9° of longitude. In 1965 this shrunk to a grid just 4° of latitude by 5° of longitude. By the 1970s computing power allowed for UCLA's smaller grid to be combined with additional levels. By 1972 the Goddard Institute for Space Studies was deploying the UCLA model with nine levels, and by the mid-1970s UCLA had expanded all the way to 12 barometric levels.

Computers were expensive, and as a consequence, innovation was contingent on continued material support from the federal government. It was no accident that two of the three

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Models: Meteorology (1946–1963) as a Case Study', *Archive for History of Exact Sciences*, 55 (2001), 395–422 <https://doi.org/10.1007/s004070000032>.

[108] I draw heavily here on Edwards, 'A Brief History of Atmospheric General Circulation Modeling'.

major research centers on atmospheric modeling in the United States were government laboratories.

Splurging on technology

To this point I have shown how the consistent government sponsorship of weather forecasting research—and in particular, numerical weather prediction—was directly tied to the innovation that came about in meteorology. The costly upper atmosphere observation network (whether kites, planes, or balloons) in the United States is directly run by the federal government's Weather Bureau, and federally funded research labs, proffered with state-of-the-art computing technology, were responsible for much of the progress in weather modeling.

That said, there are two major innovations around meteorology that have been conspicuously missing from the discussion so far: Doppler radar and meteorological satellites. These are both large systems-based technologies that require large investments to deploy, exactly the sort of technology that governments are expected to have a hand in. Weather forecasting may be even more reliant on the government providing these technologies than other industries, since there simply were no domestic buyers other than the Weather Bureau or the military. It should come as no surprise then, that Doppler radar systems for tracking precipitation and each new series of weather satellites were commissioned as a special project by the Weather Bureau, often in conjunction with NASA or the armed forces.

While most readers can probably summon a mental image of the morning weather forecast, complete with Doppler radar showing precipitation across the metropolitan area, the fact that moisture showed up on radar was a problem in its original use during World War II. The purpose for radar during the war was to track aircraft, and the interference that rain or fog would produce on the radar display significantly undermined the technology's effectiveness. While aviation research set out to find a way to filter out this interference, meteorologists who worked as radar operators returned from the war to isolate that same interference pattern and use it to measure rainfall.[109] Much of this work was done at the MIT Radiation Laboratory, funded in large part by the National Defense Research Council. The Army Air Forces Weather Service would start using weather radar in 1944.[110]

By the 1950s the Weather Bureau was deploying Doppler radar for its own purposes, mainly to supplement the data collected from rain gauges.[111] This was channeled back into the weather forecast machinery, though not as part of the predictive model. Rather, it was used to check the accuracy of regional and local forecasts.

Doppler radar likely would have never been deployed were it not for government investment. Even though weather radar is a classic story of military spin-off, it could not spin off very far. There were very few organizations that were in a position to purchase systems for weather radar. It consisted almost entirely of the meteorological services within the armed forces, and the Weather Bureau itself. Occasionally news outlets

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[109] For a general overview of radar history, see the discussion of the SAGE system in Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*; and also MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*.

[110] R. Wexler and D. Swingle, 'Radar Storm Detection', *Bulletin of the American Meteorological Society*, 28 (1947), 159–67.

[111] H.E. Landsberg, *Climatological Service Memorandum No. 98* (Washington: Weather Bureau, 1963); see also the fairly extensive list of circular letters dealing with radar operations, given in F.W. Reichelderfer, *Circular Letter No. 1-61* (Washington: Weather Bureau, 1961).

purchased single radar stations for their own local use, but this market was dwarfed by government purchases.

Satellites are quite similar in this respect, as they have until very recently been too expensive for anyone but the government to deploy them. But as meteorologist Harry Wexler explained in 1958 to the Space Science Board in the Department of Commerce, meteorological satellites offer unique data:

> "Meteorological research with satellites and rockets will provide data for all regions of the atmosphere. … Satellites can contribute because they can observe the whole world in one day or less. And by 'looking' down on the Earth, they can provide new types of data."[112]

In the late 1950s it was not entirely clear what data could be had from satellites, but there were a few ideas. At the very least, satellite photography would be able to provide world-wide cloud observations at relatively high resolution (depending on the on-board camera). This found immediate use in observing the formation of storms and providing early warning of hurricanes. From the very early days the Weather Bureau also made extensive use of satellite imagery to help in field experiments with balloon and aircraft observations.

Meteorological satellites, perhaps more significantly, fed back into the climate and weather forecasting effort. While by the mid-20th century there was a focused data collection effort in wealthy countries around the world, there was very little data about what was going on in the skies over poor countries, or crucially, over the oceans, which account for roughly

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[112] Harry Wexler, *Letter from Harry Wexler to Hugh Odishaw* (Washington, D.C., 1958).

2/3 of the surface of the planet. Meteorological satellites promised to address this. Like Wexler says in the quote above, from their position in orbit, satellites can collect data from the entire planet over the course of a day.[113] This was significant because meteorological processes are global, even when meteorological data collection is tied to national scientific infrastructures. Satellites allowed scientists to see what was going on over the oceans, but also allowed wealthy countries to fill the gaps left in the dataset by countries that could not afford the cost of weather balloon networks.

Innovation in the mid-20th century around weather forecasting was premised upon government sponsorship. This was not foreordained, though it was certainly a product of the times. As computers and electronics became increasingly less expensive, the private sector took on a larger role in developing the cutting-edge of meteorological technology and modeling.[114]

During the Cold War the US government pushed the state-of-the-art in weather forecasting far beyond what competitive markets could provide. Because government action was so aggressive, it influenced the direction that knowledge took in virtually every aspect of meteorology over this period. Researchers who were unfortunate to not be housed in a

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[113] E. M. Agee, 'Observations from Space and Thermal Convection: A Historical Perspective.', *Bulletin - American Meteorological Society*, 65.9 (1984), 938–49 <https://doi.org/10.1175/1520-0477(1984)065<0938:OFSATC>2.0.CO;2>.

[114] e.g. Vladimir Jankovic, 'Working with Weather: Atmospheric Resources, Climate Variability and the Rise of Industrial Meteorology, 1950 – 2010', *History of Meteorology*, 7.34 (2015), 23–125 <http://meteohistory.org/wp-content/uploads/2015/09/08-Vladimir-Jankovic-Working-with-Weather.pdf>; Kenneth P. Thompson, 'A Political History of U.S. Commercial Remote Sensing, 1984-2007: Conflict, Collaboration, and the Role of Knowledge in the High-TechWorld of Earth Observation Satellites', *Dissertation, Virginia Polytechnic Institute and State University*, 2007.

country that was heavily investing in meteorology, or who were simply not employed at a government laboratory or premier institution like the UCLA Department of Meteorology, simply found their work marginalized.[115]

Were it not for the federal government's consistent support for numerical weather prediction, it is very likely that the entire field of meteorology would have evolved differently, whether it would have taken another path or progressed more slowly. Of course, it is easy to see how history unfolded given the heavy investments and coordination that the government provided meteorologists in the United States. But the question of what might have happened if the government had not intervened is impossible to answer directly, since history only happens once. With that in mind, though, I will turn my attention to in-vehicle road navigation. Like weather forecasting, it demanded large-scale investments and commanded the government's attention in the decades after the Second World War. Unlike what happened with meteorology, though, the government withdrew its support, providing a window on what happens when the government chooses not to invest and first-order selection it provides to research.

In-Vehicle Road Navigation

When it comes to in-vehicle road navigation, it is difficult to establish a clear starting point. As the first subsection below discusses, not only was navigating the road system something that was of practical importance whenever long-distance travel was conducted by land, but the US government's interest in providing navigational assistance reaches all the way back

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[115] Jankovic, I.

to creation of the union. The vision for modern in-vehicle road navigation dates to the early years of the 20th century with a series of devices that linked the odometer to a scrolling paper map. But already by the 1930s a high-tech vision for the same technology had emerged, and General Motors set about to making it a reality after it became clear that the interstate highway system was on its way. The development of these smart highway technologies is the focus of the second subsection.

We want you! …to get from A to B

Navigation requires three basic things: a map, some way to figure out where someone is on that map, and a strategy for finding a good route between two points. In the early days of the automobile, for instance, motorists could buy a map from Rand McNally or the American Automobile Association and follow one of their curated routes using mile markers and route markers posted on the side of the road.[116] By the turn of the 21st century, motorists could use the digital map in their GPS device to follow the system's recommended route between A and B.

The work and technology required to provide each one of these three functions has changed considerably over time. With the period I are concerned with here, most of the innovative work happens around the question of how to pinpoint where are on our map, what I am going to call "positioning" for the rest of this chapter. What's more, this is the

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[116] James R. Akerman, 'Selling Maps, Selling Highways: Rand McNally's "Blazed Trails" Program', *Imago Mundi*, 45.1 (1993), 77–89 <https://doi.org/10.1080/03085699308592765>; John T. Bauer, 'Navigating Without Road Maps: The Early Business of Automobile Route Guide Publishing in the United States', *Proceedings of the International Cartographic Association*, 1 (2017), 1–7 <https://doi.org/10.5194/ica-proc-1-7-2018>.

fundamental contribution of GPS, the technology most readers probably equate with in-vehicle road navigation.

This is not to say that the US government was not heavily involved in producing maps or identifying routes. Far from it. It is just that most of these contributions came before the Second World War, though I will mention a few exceptions to this rule later in the chapter. When the motor vehicle emerged in the early 20th century it was private sector, not government, that assembled state-of-the-art road maps and provided route selection for drivers.[117] As policymakers and highway engineers came to value rational planning more and more, they pressured the government to intervene and seize control of road mapping and route selection from the private sector. By the 1930s, the authoritative road maps were drawn by state highway authorities, even though drivers would more often buy re-packaged versions of those maps from private companies. Around the same time, popular routes that had been selected and designated by the private sector, like the Lincoln Highway and the Dixie Highway, were replaced by route designations chosen by states and their highway engineers to represent the shortest route between major communities.

US government interest in navigation goes back to the very founding of the country. In 1807—just over 100 years before the Ford Model T started rolling off production lines—the U.S. Senate directed the Secretary of the Treasury to prepare a plan for using the power of the federal government to open roads and make canals, "which as objects of public

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[117] Andrew C. Herman, 'Inventing the Shortest Route', *Forthcoming*.

improvement, may require and deserve the aid of government."[118] Secretary Albert Gallatin responded in grand terms:

> "Good roads and canals, will shorten distances, facilitate commercial and personal intercourse, and unite by a still more intimate community of interests, the most remote quarters of the United States. No other single operation, within the power of the government, can more effectually tend to strengthen and perpetuate that union, which secures external independence, domestic peace, and internal liberty."[119]

The idea that building roads and canals held value for reasons of commerce and community was a common one in the early days of union. For the first fifty years of U.S. history, expanding the infrastructure for transportation was one of the fundamental building blocks of the government's domestic policy.

Road building and maintenance was abandoned for the remainder of the 19th century, but this interest in facilitating movement never dissipated. Throughout the 19th and 20th centuries, the US government seemingly found its purpose in providing navigational aids, whether in the form of lighthouses, nautical and aeronautical charts, radar and satellites for ships and aircraft, and of course, by the late 20th century, GPS. Many of these investments served a double purpose, as they simultaneously helped to grow US military capabilities and facilitate economic activity. This made the necessary investments an easy sell for Congress.

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[118] Albert Gallatin, *Report of the Secretary of the Treasury, On the Subject of Public Roads and Canals* (Washington D.C.: Weightman, R.C., 1808), p. 3.

[119] Gallatin, p. 8.

Even the US interstate highway system catered to both military and economic needs. The initial push for a national highway system came during the First World War, when East Coast shipyards found their train lines backed up from the massive amount of war materials that were to be delivered to France in support of the war effort. To deal with the backlog, government officials devised a plan to move a substantial amount of the rail freight by truck, given the improving status of the country's roads. Routes were carefully chosen by state and county officials so that the heavy trucks would pass over only the best roads on their way to the shipyards, but in the span of just a few weeks, hundreds of miles of high-quality roads buckled under the pressure and became utterly impassable.[120] The problem was an old one. Rain had made its way into the base of the roads through small cracks and imperfections, before weakening the roadways when they froze in the winter cold. Before freight trucking, the roads were perfect capable of standing up to the weight of passing vehicles. This prompted the Bureau of Public Roads in conjunction with the Army to begin designing a series of national highways that would be built to military requirements while also linking together major population centers in the continental United States. The result was the Pershing Map, named after General Pershing, who presented it to Congress. It detailed a series of major roads that should be built in the interest of national security, and a major inspiration for the eventual interstate highway system that was approved in 1956.

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[120] Bruce E. Seely, 'The Scientific Mystique in Engineering: Highway Research at the Bureau of Public Roads, 1918-1940', *Technology and Culture*, 25.4 (1984), 798 (pp. 802–4) <https://doi.org/10.2307/3104623>.

Developing smart highways

Momentum toward a national highway system generated excitement in the motoring community. The US government had shown a willingness to develop and build huge technological systems, and the automotive industry saw the new highway system as an opportunity to create what they called intelligent transportation systems—smart highways.

While the interstate highway system provided the motivation for pursuing smart highway technology, the underlying vision was already twenty years old, developed by architect Norman Bel Geddes over the course of the 1930s. This work culminated in the *Futurama* exhibit he created in partnership with General Motors at the 1939 New York World's Fair, but it began several years earlier. General Motors had already planned a similar diorama for the 1933 Chicago World's Fair, though it did not follow through for that event. Nor was 1939 the first time Geddes' vision was on display. He had also partnered with Shell Oil to produce a diorama of the *City of Tomorrow* for an advertising campaign that ran in 1936 and 1937.

Geddes' *City of Tomorrow* and *Futurama* exhibits were a curious blend of science fiction and standard public policy. Some parts may as well have been drawn from highway engineering manuals: Geddes' models called for separating vehicle traffic from pedestrians, minimizing intersections, providing turnaround lanes that help drivers avoid crossing the path of oncoming traffic, and so on. But Geddes also indulged in imagining technologies that did not yet exist, like automated navigation technology, and highway/vehicle systems that would allow for the central coordination and control of traffic.[121] Just two decades later, computer technology and the emergence of the routing algorithms[122] helped to make Geddes' vision technically viable.

Some of the resulting ideas were grandiose—and straight out of Geddes' vision for the future. The General Motors Research Laboratory, for instance, developed the technology for an electronic highway, calling it the Auto-Control.[123] General Motors had commissioned Geddes to design the *Futurama* exhibit, so it is not surprising that they acted so quickly to bring his ideas to life. The company touted this idea repeatedly in promotional videos as part of its traveling *Motorama* shows in the 1950s. By the end of the decade, though, company researchers had built a small-scale demonstration of the technology, meant to take over all steering and speed control, in addition to obstacle detection, on specially designed highways.[124]

Like many of the smart highway technologies put forward in this era, their goal was to "stimulate both highway and automotive research interest in an automatic highway

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[121] Automated navigation technology seems to be a favorite example of futuristic technology in the marketing world. Even in 1993, when AT&T launched its "You Will" advertising campaign, one of the commercials told viewers to imagine driving across the country without a map, and instead showing them an in-vehicle navigation device, assuring viewers that they would in fact be able to do this in the near future, and that AT&T would bring them the technology. Six decades removed from Geddes' work for Shell and General Motors, and automated navigation was still being presented as a futuristic technology.

[122] Herman.

[123] Harold M. Morrison, Albert F. Welch, and Eugene A. Hanysz, 'Automatic Highway and Driver Aid Developments', *SAE Technical Papers*, 1961 <https://doi.org/10.4271/610004>.

[124] 'Electronic "Chauffeurs" Are Possibility on Tomorrow's Highways', *Electrical Engineering*, 78.8 (1959), 875–76.

concept."[125] While the motoring public was certainly part of the audience for demonstration projects like this, the more important audience was the federal government. Smart highway technology in the late 1950s and early 1960s relied on innovative interfaces between vehicles and the road. Because the federal government especially, but to a certain extent, state governments as well, had wrested control of road construction and route designation from the private sector, any new technology that required roads to be built to specification also required explicit government approval.

The Auto-Control was no different. It promised to handle traffic and control vehicles by embedding magnetic cables in the roadbed, and having a rudimentary computer manage the interaction between the magnetic signal and vehicle control systems. Building the infrastructure needed to implement the technology meant securing government buy-in. Unfortunately, at least for the sake of smart highways, governments in the United States had never seriously considered the possibility that the interface between roads and vehicles could become the site of high-tech innovation. While federal and state governments had sorted out roles and responsibilities when it came to building roads, and designing them with safety in mind, there was not a single agency with any power concerning the vehicle/road interface. That meant that appeals from companies like General Motors did not fall on deaf ears, so much as they were simply heard by government agencies with no authority to act.

Discussions about these technologies were a regular occurrence in the complex of institutions surrounding the federal government in Washington. The year before General

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[125] 'Electronic "Chauffeurs" Are Possibility on Tomorrow's Highways', p. 875.

Motors revealed its idea for the Auto-Control, its team of engineers at the 37th Annual Meeting of the National Research Council's Highway Research Board presented a very similar concept that used wire loops in the roadbed to automatically control vehicles and manage traffic.[126] They even went so far as to conduct a (successful) field test in partnership with the Nebraska Department of Roads. But here, too, the lack of a government agency with authority over the vehicle/road interface presented a problem. Just as General Motors could not move forward with the Auto-Control without support from agencies in charge of building the roads, the engineers for the project in Nebraska noted that the government could not move forward with building roads to these specifications without buy-in from automakers, as every vehicle that was not under control of the system would pose a danger to those that were, and vice versa. As the engineers explained in the 1961 technical documentation for the system:

> "We also feel the need of closer cooperation between the automotive manufacturers and the traffic and highway engineers. Without this cooperation many good highway improvements may die in the initial hardware stages for lack of a driver testing. Hy-Com [a road condition reporting system that General Motors proposed around the same period], for instance, presents a particularly difficult problem, since road administrators will not buy one transmitter for highway installation until

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[126] V. K. Zworykin and others, 'Electronic Control of Motor Vehicles on the Highway', in *Proceedings of the Thirty-Seventh Annual Meeting of the Highway Research Board* (Washington, D.C.: Highway Research Board, 1958), pp. 436–51.

> there are receivers in the cars, and vice versa. Thus, one faces the old problem of which comes first the 'chicken or the egg'."[127]

This did not slow the overall interest in automated highways, however. RCA laboratories had been working on electronic techniques for highway vehicle control throughout the 1950s and continued to report on its progress in the early 1960s,[128] as did the team at General Motors.[129] Things were far enough along by the middle of the decade that even a team of undergraduate engineering students at the University of Michigan offered their own solution to the problem as part of their participation in the Industry Program in the College of Engineering.[130]

Around the same time, the General Motors Research Laboratories were hard at work on another idea for smart highways that they called DAIR—Driver Aid, Information, and Routing.[131] Rather than taking control away from motorists, as with the Auto-Control, DAIR rendered highways safer and more efficient by providing motorists with better

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[127] Morrison, Welch, and Hanysz, p. 50.

[128] Leslie E. Flory, 'Electronic Techniques in a System of Highway Vehicle Control', *RCA Review*, 23.3 (1962), 293–310.

[129] Keith Gardels, *Automatic Car Controls for Electronic Highways* (Warren, MI: General Motors Research Laboratories, 1960).

[130] Thomas L. Steding and others, 'The Development of an Electronically Controlled Urban Highway System: A Student Design Project', *University of Michigan, Industry Program of the College of Engineering*, 1966; Work continued late into the decade as well. See Robert E. Fenton and Karl W. Olson, 'The Electronic Highway', *IEEE Spectrum*, 6.7 (1969), 60–66 <https://doi.org/10.1109/MSPEC.1969.5213898>; A. Goldsmith and G.W. Cleven, 'Highway Electronic Systems--Today and Tomorrow', *IEEE Transactions on Vehicular Technology*, 19.1 (1970), 161–67 <https://doi.org/10.1109/T-VT.1970.23444>.

[131] Eugene A. Hanysz, 'A Communication System for Driver Aid, Information, and Routing', *SAE Technical Papers*, 1967 <https://doi.org/10.4271/670111>; E. A. Hanysz and others, 'DAIR--A New Concept in Highway Communications for Added Safety and Driving Convenience', *IEEE Transactions on Vehicular Technology*, 16.1 (1967), 33–45 <https://doi.org/10.1109/tvt.2020.3027078>.

information. In many ways, the functions that DAIR provided would be recognizable to drivers today. One aspect of the new technology, to take an example, served as an emergency communication device. As General Motors' marketing materials explained it:

> "Picture yourself on a long, lonely segment of highway. It's a rainy night, and you're trying to stretch your gasoline to the next service station. Sure enough, the engine begins to sputter. You coast to the shoulder and stop. Your wife, who suggested a stop at the last town, gives you the special look she saves for such occasions.
>
> It's a bad situation at best. But if the car is equipped with GMR DAIR, you simply dial a series of numbers on a small instrument panel. The message is received by a nearby repeater and relayed to the closest service center. A reassuring voice acknowledges the message; within a few minutes, gasoline has arrived and you're on your way again."[132]

The mythology around DAIR at the General Motors Heritage Center credits the technology with providing the basis of the OnStar system that the company launched in 1996.[133] It is not hard to see the connection: here was a system that relayed distress calls to dedicated service centers. The main difference was while OnStar relied on private call centers, the design for DAIR presumed aid and information centers that would be provided by the

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[132] General Motors Research Laboratories, *GMR DAIR System (PR-154): Driver Aid, Information and Routing* (Warren, MI, 1966), pp. 1–2.

[133] 'The Origins of OnStar', *GM Heritage Center* <https://www.gmheritagecenter.com/featured/OnStar.html> [accessed 8 August 2021].

highway authority. DAIR was billed as a “cooperative system between the individual motorist and the highway authority.”[134]

DAIR also provided a more direct informational link to the roadway by embedding magnets in the roadbed. Passing over a magnet would trigger an on-board device to deliver an audio message about traffic conditions and any emergency situations on the road ahead. It also used the same arrangement to provide routing instructions, another thing that motorists today would find familiar:

> “Suppose a motorist wants to drive to a distant city. His first stop is a nearby routing station, where he selects a route and receives a punched card for his destination. The card fits a slot in the car's DAIR console. From this point on, whenever the driver approaches a major intersection, a panel light will indicate a right turn, left turn, or straight through.”[135]

The magnets embedded in the roadbed would be encoded with identifying information on the approaching intersection, and as a vehicle passed over them, they would communicate with the in-vehicle computer to provide live turn-by-turn instructions.

Providing turn-by-turn instructions was a novelty in itself. Just as computers transformed weather forecasting as they made gains in memory and computational power, the same thing was true for route selection. The core insight for route selection goes all the way back to 1736 when mathematician Leonhard Euler showed that road system (or in his case, the

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[134] Hanysz and others, p. 33.

[135] Laboratories, p. 3.

system of bridges in Königsberg's city center) could be represented as a network. This is a boon for all sorts of technical questions because representing the road system in this way means that graph theory and linear algebra can be used in producing solutions.

The newfound availability of computers in the 1950s, as was the case in weather forecasting, allowed mathematicians and network scientists to compute all sorts of things that had so far been impractical. One of the most important advances from this period was the creation of our standard algorithms for finding the shortest path between two points in a network.

In 1956, for instance, new PhD-holder Edsger Dijkstra was asked to provide a simple demonstration problem for a newly-upgraded version of the first Dutch computer, to help non-experts understand the machine's value.[136,137] So he assembled a simplified road map of the Netherlands with 64 cities, and designed an algorithm—according to his story, in twenty minutes while drinking coffee with his fiancée at a café in Amsterdam—that would find the shortest path between any two cities.[138] This algorithm not only provided a successful demonstration of the new computer, it was also immensely important scientifically. Known today as the Dijkstra algorithm,[139] it still forms the basis for most

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[136] Thomas J. Misa, 'Interview: An Interview with Edsger W. Dijkstra', *Communications of the ACM*, 53.8 (2010), 41–47 (p. 42) <https://doi.org/10.1145/1787234.1787249>.

[137] For another example of how closely the developments in this area were tied to the rise of computers, note as well the subtitle of the Bureau of Public Road's *Traffic Assignment Manual*, which puts the matter into clear relief: "For Application with a Large, High Speed Computer."

[138] Misa, p. 42.

[139] E. W. Dijkstra, 'A Note on Two Problems in Connexion with Graphs', *Numerische Mathematik*, 1 (1959), 269–71.

path-finding methods in network science, and its simplified form, breadth-first search, is a regular feature on undergraduate syllabi. Nor was Dijkstra alone. At the RAND corporation in Santa Monica, Lester Ford Jr. published a similar algorithm in 1956, as did his colleague Robert Bellman in 1958.[140] One year later, and on the other side of the country at Bell Labs, Edward Moore published yet another modification of their work.[141]

In just the span of a few years toward the end of the 1950s, the two major path-finding algorithms—Dijkstra's algorithm and the Bellman-Ford-Moore algorithm—were developed. This made it possible for transportation planners to employ an entirely automated approach to assigning traffic to routes. Indeed, just a few years later in 1964, when the Bureau of Public Roads published its *Traffic Assignment Manual*, it gave credit to Moore and a fellow named George Dantzig, who wrote his own piece in 1957 on the shortest route problem,[142] for transforming the field.[143]

For the second time in a decade, in any case, General Motors had viable smart highway technology but needed federal and state agencies to pay the cost, in part because the company could not tear up roadways on their own authority just to install magnets. Even the technical documentation presented the company's case for government readers. It

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[140] Lester R. Ford Jr., *Network Flow Theory, Paper P-923* (Santa Monica: RAND Corporation, 1956); Richard Bellman, 'On a Routing Problem', *Quarterly of Applied Mathematics*, 16 (1958), 87–90 <https://doi.org/10.1090/qam/102435>.

[141] Edward F. Moore, 'The Shortest Path through a Maze', *Proceedings of the International Symposium on Switching Theory*, 2 (1957), 285–92.

[142] George B. Dantzig, 'The Shortest Route Problem', *Operations Research*, 5 (1957), 270–73.

[143] *Traffic Assignment Manual: For Application with a Large, High Speed Computer* (Washington, D.C.: Bureau of Public Roads, 1964), pp. I–3.

pointed out that "magnets were chosen because they provide a passive, maintenance free installation which is low in material cost and easily installed in old or new pavement,"[144] and that "with over a million CB transceivers in the hands of the motoring public, two-way voice communications is already possible with stations controlled by highway agencies."[145] This provided what General Motors called a "building block" approach, where motorists would be able to immediately, and economically, make use of any highway authority installation.

Other materials read like a menu. They highlight where descriptions can be found for those systems and facilities that needed to be provided by government,[146] and explain that added functions could be provided "at an additional cost to the highway authority."[147] General Motors believed its technology was viable, and that it just needed to convince the right people to get it built. As it turned out, General Motors was not wrong. But neither did things work out the way it was hoping for.

The US government became interested in the problem of congestion and routing late in the 1960s. Congress' special subcommittee on the Federal-Aid Highway Program, for instance, held special hearings on the issue in 1968.[148] Around the same time the Bureau of Public

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[144] Hanysz and others, p. 33.

[145] Hanysz and others, p. 37.

[146] Hanysz, p. 4.

[147] Hanysz, p. 6.

[148] *'Highway Safety, Design and Operations; Freeway Signing and Reduced Congestion Related Geometrics,' Hearings before the Special Subcommittee on the Federal Aid Highway Program* (Washington, D.C.: U.S. Government Printing Office, 1968).

Roads launched an R&D project for what it called the Electronic Route-Guidance System (ERGS), which bore remarkable similarities with the technology that General Motors had been pushing over the previous decade.[149] It consisted of a series of roadside computers that would communicate navigation instructions to drivers thanks to magnetic loops embedded in the roadbed.

By this time the Bureau of Public Roads had assembled an impressive research team, made up of several former NASA engineers who had considerable experience with high-tech system thanks to the space race.[150] But the ERGS drew heavily on industry expertise as well. The digital map at the heart of the system, which like other digital maps at the time represented the road system as a network, was designed by Philco-Ford. Ford, of course, already had a wealth of knowledge about motor vehicle design and assembly. But it had also recently acquired the Philco company, which was a consistent innovator in transistor technology in the 1950s. Philco-Ford leveraged their electronics and production capabilities to become the prime contractor for NASA's Mission Control Center in Houston and secured several other contracts with the Apollo missions. Contracting the digital map to Philco-Ford meant that the Bureau of Public Roads could draw on that same expertise.

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[149] Dan A. Rosen, Frank J. Mammano, and Rinaldo Favout, 'An Electronic Route-Guidance System for Highway Vehicles', *IEEE Transactions on Vehicular Technology*, VT-19.1 (1970), 143–52 <https://doi.org/10.1109/T-VT.1970.23442>; cf. Hans K. Klein, 'Institutions, Innovation, and Information Infrastructure: The Social Construction of Intelligent Transportation Systems in the U.S., Europe, and Japan' (Massachusetts Institute of Technology, 1996).

[150] Lyle Saxton, *Mobility 2000 and the Roots of IVHS* (Washington, D.C., 1993), pp. 1–2.

ERGS was also contracted in part to General Motors itself, which was slated to provide hardware technology.[151] This was likely the same components that GM had been developing and advertising throughout the 1960s, or at least upgraded versions of them. What marked out ERGS from DAIR was that in the original General Motors design drivers would need to travel to a particular location to enter their destination and get directions, while the system proposed by the Bureau of Public Roads was more ambitious. By putting computers on the roadside, drivers could get directions on-the-go, without needing a detour to visit a computer hub.

In 1968 the Bureau of Public Roads tested the ERGS at an intersection in Washington, D.C., and had plans in 1969 to expand the test to more than 100 roadside units spread out across the capital suburbs in Maryland and Virginia. They even did rudimentary market testing to see if drivers would like a system like this, showing a film called "Guiding Tomorrow's Motorist" at the Smithsonian that documented the system, and conducting a survey of 1500 visitors.[152] Everything suggested that the system was technically viable—as General Motors already suspected when it came to DAIR—and that motorists were interested in the technology, with large numbers of survey respondents indicating that they would purchase the necessary in-vehicle devices themselves.

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[151] Rosen, Mammano, and Favout, p. 148.

[152] Rosen, Mammano, and Favout, p. 146.

Come 1971, Congress chose not to authorize any more funding for the project. The result was R&D and human capital was redirected toward topics that had government support, or where market support was strong enough that industry could act more independently.

In-vehicle road navigation for the GPS era

The withdrawal of government support from smart highway technology had a long-lasting legacy. It would take until the mid-1990s for in-vehicle road navigation to re-emerge as a viable technology. The reason for this gap is that satellite-based navigation technology is structured differently from the smart highway systems that were just discussed. Without roadside computers to hold the internal map in memory and to compute the shortest route, those burdens fall on the in-vehicle receiver. Electronics were impressive already in the early 1970s, but it would still take some time before they were small enough and inexpensive enough to make in-vehicle road navigation possible. By declining to build the expensive infrastructure that was necessary for DAIR and ERGS, the federal government effectively put a stop to the technology before it had even been deployed for general use.

Because the nature of the technology and the prevailing attitudes about how government should be involved in the economy changed over the ensuing decades, satellite-based road navigation is not a reasonable comparison with the other examples I have considered in this chapter. I return in Chapter 4 to consider what role the government played in the development of in-vehicle road navigation that was organized around satellites.

Innovation around in-vehicle road navigation—in the mid-20th century at least—depended on government support. Companies like RCA and General Motors certainly began developing smart highway technologies before the government became directly involved in R&D. But this movement was premised on the massive investments the government was making into the interstate highway system. Because of the inherent cost in a system as ambitious as the magnetic wire technology the companies were proposing, only the government could reasonably cover the necessary costs.

When the federal government withdrew its material support from the ERGS project at the Bureau of Public Roads, already fifteen years into the construction of the interstate highway system as well, industry's hopes of securing the necessary funding to pursue smart highways evaporated. General Motors continued to show interest in in-vehicle road navigation over the coming decade, as Chapter 4 explains, but it was by and large unwilling to invest considerable resources (or take on risk) in developing technology that was unlikely to be adopted.

	Cost of necessary infrastructure	Technology benefits military	Government laboratories involved in R&D	Government is the intended provider	Government interest in the technology	System Adopted or Abandoned
Weather Forecasting						
Upper Atmosphere Network	High	Directly	Directly	Yes	Consistent	Adopted
Radar	High	Minimally	Directly	Yes	Consistent	Adopted
Meteorological Satellites	High	Indirectly	Directly	Yes	Consistent	Adopted
In-Vehicle Road Navigation						
Magnetic wire systems	High	Minimally	Directly	Yes	Sporadic	Abandoned
Pattern with respect to adoption and abandonment	**None**	**None**	**None**	**None**	**Direct relationship**	

Table 2: Government sponsorship is a necessary cause of system adoption. *Note that there is no clear pattern between the adoption or abandonment of the technology and its cost, whether the technology benefits the military, whether the government is directly involved in producing the R&D through its own laboratories, or whether the government is the intended provider of the technology.*

Picking and choosing

From the Second World War up through the early 1970s the United States government took aggressive action to boost scientific research and bring cutting-edge technologies to its military and the general population. In most important ways this period was characterized by the computer. Our world is still characterized by the computer, of course, but what makes the early Cold War so unique is that computers had made possible all sorts of transformative technologies. Just in the two cases considered here, ENIAC brought Richardson's forecast factory to life, minus 64,000 mathematicians, and roadside computers made in-vehicle navigation systems like DAIR and ERGS a possibility, even though they were never realized.

But at the same time computers were still large and expensive, making this sort of technology difficult for anyone but the government to take advantage of. In the end, it was the US government that pushed new technology into weather forecasting and generated industrial R&D in smart highway systems through its large investments into the interstate system. It was equally the US government that terminated the line of research around smart highways in the early 1970s when it withdrew funding. As the summary in Table 2 highlights, consistent support from the government appears to be a necessary cause for R&D around given technologies and for their deployment. This offers strong evidence for what Dosi called this the "first-order selection" of research trajectories,[153] in the sense that

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[153] Dosi.

applied researchers are not very likely to pursue projects that they know will never amount to anything because there is no market for it.

One potential objection is that maybe weather forecasting ended up as a monopsony in the United States because it served the military, and the military-industrial complex is perhaps the best example of a monopsony.[154] NASA and the space race have long been seen as the one notable exception, but even there, the geopolitical strategy behind the Apollo missions (for instance) suggests that it is only a stone's throw away from being military R&D.

All this being said, the two cases in this dissertation stand out from these examples. To be sure, the military benefits from good weather forecasts much as civilians do, and there is probably some small benefit from an in-vehicle navigation system as well. But there is very little geo-political pressure to push research forward in these areas. As the next two chapters document, the US government was not pursuing these technologies for competitive advantage. On the contrary, it shared these technologies with other countries. While military benefits may have helped Congress justify the costs, the power that governments had to start and end research in these areas was not bound up with military, but with the simple fact that the systems technology of the era relied on computers, and they were too expensive and expansive for anyone but the government to build. It was effectively a market with just one buyer—a monopsony—and it behaved as such.

This is still just a starting point for understanding how governments affect the accumulation of knowledge and the evolution of technology. First-order selection is an

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[154] Mowery, II.

example of the kind of process that Michael Polanyi had in mind when he railed against government intervention in the “spontaneous order” of science. But as I mentioned in Chapter 1, governments are just as capable of influencing scientific research by changing the fundamental possibilities for innovation by introducing new technologies. Chapters 3 and 4 shift the focus to explore exactly this issue.

Chapter 3:

When is a picture worth a thousand data points?

Introduction

I have set out to study how much power governments have to disrupt the "spontaneous order" in science.[155] If scientists, when left alone, collectively veer toward the best research topics, does government intervention lead them astray and forego innovations that may have benefited the world? In the previous chapter I showed that the US government was decisive in channeling research toward weather forecasting and smart highways, and even terminated the research into the latter after Congress decided to withdraw funding.

This reflects one of the two mechanisms I described in Chapter 1 for how governments can impact the topics that are prioritized in scientific research. Recall I drew the comparison with thousands of expeditions setting out to find the tallest mountain. What Chapter 2 illustrated was the government's ability to reallocate research teams to specific parts of the landscape. Economists have called this "picking and choosing," since the government is betting that it can make an intelligent decision about which areas to focus on.[156]

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[155] Michael Polanyi.

[156] Nelson and Langlois.

The present chapter offers my first foray into documenting the second mechanism, which resembled more the case where governments shifted the landscape itself, making some mountains taller and some valleys deeper. In this way the government does not disrupt science's spontaneous order, so much as it changes what the right answer happens to be.

Examining how much government interventions affect the incentives for researchers to choose one topic over another, as opposed to shaping the underlying landscape, requires that I spend more time looking at the reception of new technology within the meteorological community. What this chapter shows is that the government does not always succeed when it tries to reallocate research toward specific, making it a little questionable to call the government a disruptive force. More interesting is that even when the government appears to have made the wrong choice in which technology to sponsor around weather forecasting, scientists picked up the slack and found uses for the new technology anyway. The spontaneous order in science seemed unperturbed by government intervention.

Meanwhile, in the cases where intervention was a clear success, this occurred less by luring researchers from one topic to another, and more through changing the fundamental possibilities for research by removing key roadblocks with technology. Weather forecasting moved forward thanks to government interventions that amplified existing research. There is very little evidence that it disrupted the spontaneous order in science.

Expanding the forecast factory

20th century meteorology was a field built on cutting-edge technology, and weather forecasting was a practice built on the same. Here for instance is Helmut Landsberg, the Director of Climatology at the Weather Bureau, in 1962:

> "In all these efforts the finest measuring devices are needed. Much electronic gear is at hand but the end is not in sight. Similarly, the large-scale electronic computer has been engaged in tying observations together into a coherent net. Causes and effects are being unravelled and with mathematical tools today's events are being projected into the future. At present it is still an uncertain future. The observations are incomplete, the chain of sequences has missing links, the mathematical puzzles are only partially solved"[157]

Already in 1962 Landsberg was highlighting the role of new technology like "electronic gear" and computers in transforming the possibilities for numerical weather prediction, while also noting that technology had not solved everything.

I start here with two of the most fundamental technologies for numerical weather prediction, weather balloons and computers. The latter technology was mentioned explicitly in the quote above, though the "finest measuring devices" is likely a reference to weather balloons, at least in part. What is significant is that these technologies were each implemented thanks to outsized investments from the federal government.

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[157] H.E. Landsberg, *Climatological Service Memorandum No. 85* (Washington: Weather Bureau, 1961).

Furthermore, as I will show in the two subsections below, both weather balloons and computers transformed the possibilities for research. Yes, researchers found themselves drawn to numerical weather prediction in the wake of the government's intervention. But this was not because the government had distorted the incentives among scientists. Rather, weather balloons and computers overcame the main stumbling blocks for numerical weather prediction.

Weather balloons

As I already discussed in Chapter 2, the advent of numerical weather prediction had a profound effect on the kinds of weather data that were collected in the early 20th century. The main realization was that since weather patterns are produced by dynamics in the atmosphere, researchers needed to collect data from the atmosphere itself rather than relying on measurements that were taken on the surface of the earth.

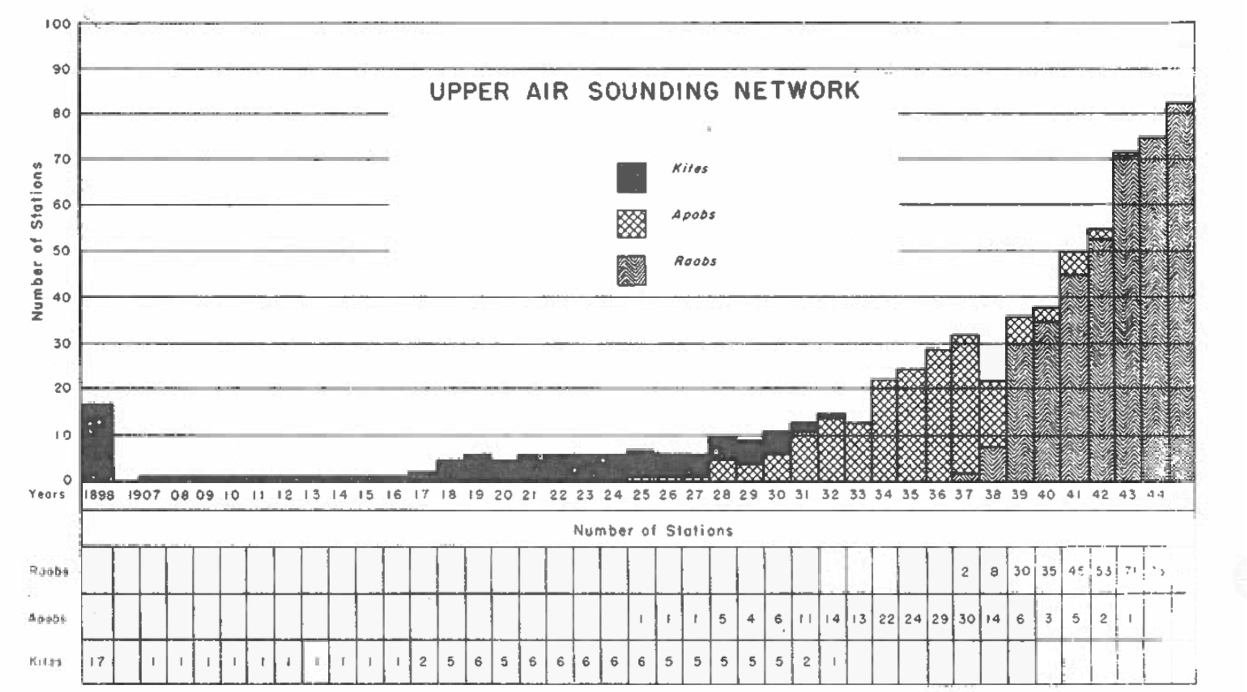

Figure 1: Changing technology in the upper atmospheric sounding network at the US Weather Bureau from 1896 to 1945*. Apobs stands for airplane observations, while Roobs stands for radiosonde (weather balloon) observations. While upper-air observations were seen as crucial from a very early date, kite observations were not able to reach an elevated enough height. Chart is taken from the US Weather Bureau's Climatological Service Memorandum No. 50, November 23, 1955.*

Figure 1 shows how rapidly the formal network of upper atmosphere sounding stations expanded as new technologies emerged. Before the airplane it was kites that dominated efforts to collect data on the temperature, pressure, and humidity in the sky. Kites unfortunately turned out to be ill-suited to the task since they could not reach high enough into the atmosphere. By the late 1920s, though, a new strategy had emerged. Airplanes would carry virtually the same meteorograph—an automatic recording device for (usually) temperature, pressure, and humidity—that kites had been carrying aloft.[158] Meanwhile, balloons were launched without any equipment attached for the sake of estimating the wind speed. These "free balloons" would be released and tracked from the ground using a theodolite and some simple mathematics would provide a rough estimate of the wind speed at different altitudes.

The fundamental problem with using free balloons for collecting weather data is the same one that exists for children at a birthday party: balloons have an unfortunate tendency to fly away. Already in the late 19th century, French meteorologists had experimented with balloonsondes, balloons that carried self-registering thermometers and barometers. But because they would get caught in the wind and carried off in unpredictable directions, it could take days to recover them if they were recovered at all.[159,160] If the balloon was never found, whatever price was paid for the equipment would be lost and the data it collected along with it. Even in the happy circumstances where the balloons were successfully retrieved, there was no guarantee that the data could be used in time for a weather forecast. By launching free balloons—that is, without any equipment attached—wind data

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[158] Alan C. Bemis, 'Aircraft Meteorological Instruments', in *Compendium of Meteorology* (Boston: American Meteorological Society, 1951), pp. 1223–31.

[159] John L. DuBois, 'Invention and Development of the Radiosonde with a Catalog of Upper-Atmospheric Telemetering Probes in the National Museum of American History, Smithsonian Institution', *Smithsonian Studies in History and Technology*, 53, 2002, 1–78 (p. 3) <https://doi.org/10.5479/si.00810258.53.1>.

[160] This, it should be said, is the basic limitation to weather balloons as data collection devices. Even today the US National Weather Service reports that only 20% of the weather balloons they launch ever get found and returned.

at least could be collected from the ground without worrying about if the balloon would be recovered or not.[161]

Radio changed the possibilities for weather balloons. By attaching radio equipment to a balloon, data could be relayed back to the meteorologist on the ground almost immediately, even if the balloon were lost. The result was the "radiosonde." The key advances in radio circuitry and telemetry came in the late 1920s, prompting governments around the world to begin purchasing radiosondes from inventors like Vilho Visala in Finland, or to commission their own radiosonde designs. In the United States, the government had the Army Signal Corps—which had long overseen the Weather Bureau in the 19th century—to design radiosondes for use in the upper air network. As you can see in Figure 1, radiosondes almost completely replaced airplanes in the Weather Bureau's sounding network in the three years from 1937 to 1939.

With the technological developments that were brought about by the Second World War, radiosondes took another leap forward. Here the story finally gets back to the powerful post-war American state, highlighting the contrast with technologies like radar and satellites that I will be considering later. Interestingly, radar provides the big change for weather balloons as well.

Radar made it is possible to track the flight of radiosondes and to estimate the wind speed using its flight path. These "rawinsondes," short for radar and wind sonde, combined functions that had long been separated. I mentioned a moment ago that meteorologists

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[161] W. E. Knowles Middleton, *Invention of the Meteorological Instruments* (Baltimore: Johns Hopkins University Press, 1969), pp. 99–100.

would track free balloons to estimate the wind speed, while collecting temperature, pressure, and humidity readings using airplanes. Rawinsondes accomplished both, though the wind finding process resembled the older theodolite approach in its underlying mathematics.[162]

These innovations were adopted almost immediately across the entire US upper air observation network, and it was done without fanfare or controversy. This was also the case when tracking was automated using advancing computer technology in the 1970s and when tracking moved to satellite systems like GPS later on. The only evidence I could find that these innovations posed any difficulty at all is in the procedure manuals issued by the Weather Bureau, which of course needed to be updated every time there was a transition to new equipment.[163]

Otherwise, the main internal debates around weather balloons focused on government decisions to move or decommission rawinsonde stations. Recall from the previous chapter that the upper air stations were arranged strategically across the country: weather balloons were meant to provide the starting data for grid models in numerical weather prediction. Stations are spaced roughly 250km to 350km apart across the continental United States in an effort to do just that.

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[162] Richard Pettifer, 'From Observations to Forecasts - Part 2. The Development of in Situ Upper Air Measurements', *Weather*, 64.11 (2009), 302–8 <https://doi.org/10.1002/wea.484>; DuBois.

[163] e.g. Office of the Federal Coordinator for Meteorological Services and Support Research, *Federal Meteorological Handbook No. 3, Rawinsonde and Pibal Observations* (Washington, D.C.: National Oceanic and Atmospheric Administration, 1997).

There is usually no need to move an upper air station except to improve its location for technical or logistical reasons.[164] Even though grid sizes in weather models got smaller as computers became more powerful, statistical techniques improved as well, allowing for better estimates of what the temperature was at each precise grid point. This meant that the network that existed already in 1945 was sufficient for the needs of weather forecasting models all the way to the turn of 21st century. In Figure 1 you can see that there were 82 stations in the upper air network as of 1945. While the number fluctuated somewhat over time, by 2020 the upper air network still only had 92 stations, the bulk of which were housed at their original locations.

Small controversies developed from time to time as cost or politics forced the closure or relocation of stations that scientists saw as being valuable on technical grounds. Most of these debates left no paper trail, as they tended not to spill over into larger professional or public forums.[165]

Weather balloons and their observation network provided a natural link with numerical weather prediction practices. They were expensive to maintain, costing $200 per balloon and with several launches a day at over 80 stations around the country—and again, most of

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[164] By the 1960s there was also an awareness that keeping the upper air stations where they were was beneficial for historical or long-term studies of the atmosphere. When stations were moved, data often become incommensurable, undermining the ability to study how weather patterns have changed over time.

[165] While there was no paper trail, I conducted several expert interviews at the National Weather Service in Silver Spring, Maryland, each of which attested to the existence of these small, intermittent controversies. One situation that was brought up on more than one occasion was the 1988 decision to shut down the radiosonde station at Barter Island on the far northern tip of Alaska. Its position at the far north meant that Barter Island provided high-leverage data points for numerical weather prediction models. But it also meant that staffing and supplying the station was expensive. Budgetary cutbacks forced the shutdown of the station, despite some vocal opposition from the modeling community.

these balloons are never recovered. This amounted to about $10 million per year for the entire network. Innovations to weather balloon technology were adopted almost immediately, as the data were easily incorporated into existing models and forecasting practices. In fact, they were designed to be so. Changes to the network represented a larger disruption and the bigger source of friction, rather than innovation itself, since it was disrupting the close relationship between model and data.[166]

Far from introducing friction, the main moments where weather balloons get discussed during a controversy is when there are calls to de-emphasize satellites in favor of getting more balloon launches, something I will discuss later in this chapter. Weather balloons show the government exercising its largest impact in meteorology, providing technology and data collection that otherwise would not be provided, and allowing for more advanced weather forecasting models to be deployed as a consequence.

Punch cards and computers

In the previous chapter I mentioned that the area where government sponsorship had the largest impact on weather forecasting was computing. The investments made by the US into computer technology after WW2 were staggering. And it was not just computers, but the entire infrastructure around them. The government regularly purchased top of the line computers for use at the Weather Bureau, but it also created some of the largest data warehouses in the world. This was a substantial undertaking in the 1950s, as data storage

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[166] Changes to the network have also created a decades-long metadata crisis within meteorology, as long-term processes can only be studied with historical data. When stations move locations or they change technology without documenting it, it severely undermines the ability of researchers to track historical changes in the climate, as it makes data points difficult to compare.

was handled using punch cards. It meant that whenever someone took a weather reading, regardless of if it was at the surface or in the upper atmosphere, it needed to be written down and eventually turned into a machine-readable punch card. All that paper needed to be stored somewhere. Just as the social security building turned into a massive warehouse of data files,[167] so too did the Weather Bureau turn into a massive warehousing project in order to support the computerization of atmospheric research and forecasting, all funded by the federal government.

Punch card mechanization was adopted by the Weather Bureau in 1948,[168] even before Reichelderfer, the Bureau's Chief, encountered ENIAC at the Institute for Advanced Studies and suggested using the computer to run a weather forecast.[169] The switch to punch cards was part of a Weather Bureau initiative called the Climatological Service Improvement Program. As Merrill Bernard, the Chief of Climatological and Hydrologic Services explained, there was a sense that the Second World War had exposed how little progress had been made with numerical weather prediction:

> "It became evident during the war that the Bureau had lost ground in its climatological service program. One of the reasons for this loss of ground was the growing impossibility to manually handle the increasing volume of records which the Weather Bureau now currently collects. The other reason was the Bureau's

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[167] Dan Bouk, 'The National Data Center and the Rise of the Data Double', *Historical Studies in the Natural Sciences*, 48.5 (2018), 627–36 <https://doi.org/10.1525/hsns.2018.48.5.627>.

[168] Merrill Bernard, *Climatological Service Memorandum No. 1* (Washington: Weather Bureau, 1948).

[169] Harper, chap. 4.

> inability to develop and apply new techniques to the solution of climatological problems. The second reason was in part brought about by the first reason."[170]

The Climatological Service Improvement Program was meant to tackle both issues that Bernard raised. It would push forward the analytical techniques around numerical weather prediction, and to help do so it would mechanize the Bureau's data handling processes. The hope was that early mechanical—as opposed to digital—computers would evolve fast enough in the coming years so as to make some aspects of numerical weather prediction feasible.

Since the end of the Second World War, the US Navy had been storing its own punch cards in a warehouse at the Embarken Port in New Orleans. It came to an agreement with the Weather Bureau to share that space as part of the latter's new initiative toward mechanization. But only two years after the Weather Bureau started its switch to punch cards, the facility at Embarken Port was running out of space. Congress responded by authorizing the creation of a new National Weather Records Center in Asheville, North Carolina, a facility that Landsberg would later call "the Mecca of climatologists around the world."[171] As of 1959 the scale of the operation was staggering. Here is Landsberg again, explaining the impact of the new facility:

> "This resulted in the greatest collection of weather data that the world has ever seen. Every effort has been made to ensure that at least a copy of all available

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[170] Bernard, p. 1.

[171] H.E. Landsberg, *Climatological Services Memorandum No. 93* (Washington, D.C.: Weather Bureau, 1962).

> meteorological records collected in the United States and its possessions is stored at this depository. This requires approximately 175,000 square feet of floor space. Approximately 350,000,000 punch cards, containing weather data, are housed and serviced. These files are growing at the rate of about 30,000,000 cards per year. The Center is equipped with a full array of electric accounting machines and in addition now makes use of four digital computers. The Weather Bureau portion of the unit consists presently of six separate sections which comprise a staff of 356 people."[172]

As the quote indicates, while punch card storage began at the Weather Bureau with mechanical computers in mind, by 1959—just nine years after the weather forecast experiment on ENIAC—digital computers had become a key component to the Bureau's plans, with four housed in the Asheville facility alone. The adoption of digital computers came relatively quickly.

Already in 1955, the Weather Bureau made it a point to highlight their newly acquired ALWAC computer to members of the National Research Council's Advisory Committee on Climatology who were touring the Asheville facility at the government's behest.[173] As of 1957 the Weather Bureau was telling its climatologists across the country that electronic computers would soon be able to produce forecasts using numerical weather prediction, and that there needed to be discussion about whether data collection efforts needed to be expanded to take advantage of the newfound computational power.[174] Because

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[172] H.E. Landsberg, *Climatological Service Memorandum No. 73* (Washington: Weather Bureau, 1959), p. 15.

[173] H.E. Landsberg, *Climatological Service Memorandum No. 53* (Washington, D.C.: Weather Bureau, 1956), pp. 3–4.

[174] H.E. Landsberg, *Climatological Service Memorandum No. 62* (Washington, D.C.: Weather Bureau, 1957).

computational power was growing so rapidly, the Weather Bureau purchased new computers in 1961,[175] this time Minneapolis-Honeywell 800 units. They were operational two years later.[176]

Computers (and the mechanization of data) served to amplify R&D around weather forecasting. As I discussed in Chapter 2, the development of more sophisticated forecasting models was closely tied to computational power. Weather forecasting could only incorporate additional vertical layers and decrease the grid size in its models if computers were powerful enough to handle it.

So far as I can tell, no serious objections were ever made to these purchases. It was taken for granted that the investment would pay off in terms of the long-term accumulation of knowledge and its impact on the economy. In the early 1960s the federal government was even considering developing specialized computers for meteorology, prompting the Interdepartmental Committee for Atmospheric Sciences to explain that this was unnecessary.[177]

Weather balloons and computer technology show that it is possible for governments to have a large and direct impact on the accumulation of knowledge. In each case, innovations were adopted quickly and without dispute since they complemented the goals of numerical

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[175] Landsberg, *Climatological Service Memorandum No. 85*.

[176] H.E. Landsberg, *Climatological Services Memorandum, No. 103* (Washington, DC: Weather Bureau, 1964).

[177] Federal Council for Science and Technology, *Minutes and Record of Actions for the Meeting of June 23, 1964* (Washington, D.C., 1964), p. 4.

weather prediction. But this is not the story that critics of government intervention would expect. These technologies were fundamental to making numerical weather prediction into a viable scientific project. Without the help of government intervention in overcoming the basic roadblocks of upper atmosphere data and computing power, it is entirely possible that numerical weather forecasts are delayed for several decades in the same way that in-vehicle road navigation technology was.

What this implies is that while the government certainly attracted research toward the topic of numerical weather prediction, it did so by changing the fundamental possibilities in the scientific landscape. It made the mountain of numerical weather prediction taller, so to speak. By contrast, if numerical weather prediction had been the beneficiary of the government disrupting the spontaneous order in meteorology, there would have been more conflict as researchers were corralled from their preferred topic to the one the government wanted them to work on. Incidentally, this is precisely what happens when the government introduced radar and satellites to the socio-technical system around weather forecasting.

How useful is a picture?

Radar and satellites stand in sharp contrast to the previous technology. The government was again bringing state-of-the-art technology to the field, but it wasn't nearly as fruitful in the initial rollout. In part this was because government was being pushed by the emergence of new technology.[178] But this was also true for computers. The larger factor was the ease

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[178] On the idea of push and pull factors, see Rosenberg; Dosi.

with which scientists could make use of the innovations to build on their existing work. Computers amplified a longstanding project in meteorology, namely, numerical weather prediction. Radar and satellites presented a challenge in that regard, as they provided data in the form of pictures rather than numbers.

This is not to say that researchers were not excited about the possibilities that radar and satellites presented to weather forecasting, not to mention to the larger meteorological community. The promise of the two technologies seemed apparent to everyone. They provided data over a large radius, and in the case of satellites, regardless of where Weather Bureau stations or contractors were located. Radiosondes could not collect data over the ocean in a systematic way as they could over land. Both radar and satellites could do exactly that. Radiosondes also could not be counted on to provide data in countries that were not wealthy enough to afford the cost of an upper atmosphere sounding program. Satellites provided global coverage.

Nonetheless, researchers struggled to make use of the government's investment in radar and satellites for quite some time. And despite the larger promise that satellite technology held, its struggles lasted much longer and prompted more consternation. The difference was that even though both radar and satellites provided pictures as data, the pictures gleaned from radar were easier to turn into numbers—and easier to absorb into numerical weather forecasting—than those taken by satellite.

Radar

I mentioned in Chapter 2 that the discovery that radar could be used in meteorology goes back to the Second World War and the realization that the noise that was interfering with operators' ability to track aircraft was coming from clouds and rainfall. The principle behind radar is twofold. First, a pulse of radio waves is transmitted in all directions, and those radio waves bounce off objects when they run into them. Some of those radio waves bounce straight back to where they came from, allowing a receiver to identify an object's location by counting the time between the moment of the initial pulse and the moment the radio waves returned. If water drops were large enough, they too could reflect the radio waves, complicating the effort to track aircraft but also enabling the tracking of storms. Doppler radar systems add the ability to track movement speed and direction using the Doppler effect.

Even before the Second World War had concluded, the Army Air Force took radar systems designed by Bell Laboratories and the MIT Radiation Laboratory for direct military applications and began installing them for the sake of weather surveillance in the Pacific Theater. Panama and India consequently had the world's first weather radar networks.[179] While these systems provided value, they were crude. The radio waves emitted by these systems lost much of their strength as they encountered water, making it extremely difficult to detect anything beyond the first layer of raindrops that the pulse encountered.[180] When the Weather Bureau received 25 radar systems from the Navy in 1946, one of its first tasks was to adjust the wavelength of the emitted pulses to reduce the

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[179] Roger C. Whiton and others, 'History of Operational Use of Weather Radar by U.S. Weather Services. Part II: Development of Operational Doppler Weather Radars', *Weather and Forecasting*, 13.2 (1998), 244–52 (pp. 221–22) <https://doi.org/10.1175/1520-0434(1998)013<0244:HOOUOW>2.0.CO;2>.

[180] c.f. David Atlas and Harold C. Banks, 'The Interpretation of Microwave Reflections from Rainfall', *Journal of Meteorology*, 8.5 (1951), 271–82.

attenuation of the signal strength.[181] The result was the first civilian weather radar in the United States. Several units were already installed by the end of 1947, with priority given to major airports and to regions with severe storms. The second radar installation was made at the Weather Bureau field office in Wichita, for instance, in the middle of Tornado Alley.

This early form of weather radar found its use in tracking storms that had already formed, rather than in weather forecasting. The most dramatic example of this, in the true sense of the word, came in 1961 when a young Dan Rather—known mainly for being the CBS evening news anchor later in his career, and who at the time was working for the network's affiliate in Houston—overlaid radar output on a map of the Gulf of Mexico to show the expected path of Hurricane Carla in his report, helping to accelerate the evacuation of Galveston. This turned out to be the first use of radar on live television. Meteorologists knew of the potential for storm tracking for more than a decade before that, however.[182] By the early 1950s it was common to use radar to identify the early formation of thunderstorms and tornados, both of which often leave a distinctive hook pattern on radar, to issue early-notice emergency weather alerts.

Of course, the data was still just made up of images. This made it difficult to share with people who were not present at the radar station. To deal with this the Weather Bureau embedded weather service personnel at the airports and weather stations that houses

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[181] Whiton and others, p. 222.

[182] e.g. Wexler and Swingle; For a more general history of this use of radar, see also David Atlas, *Radar in Meteorology* (Boston: American Meteorological Society, 1990).

radar units. They would hand-draw what was on the radar display so it could be sent by fax to Weather Bureau offices around the country.[183] The Weather Bureau office in Kansas City took it upon itself to assemble a national radar map with the resulting set of radar reports. In its first iteration the radar output was drawn on a Plexiglas overlay that lay in front of a large map that was posted to an office wall. The map itself was so large that one worker needed to use a ladder to draw the conditions in the northernmost parts of the country. After a few years the Kansas City office switched to producing the national radar map on paper. It was not until the 1975 that the process could be automated with computers.[184]

The national radar map was used to great effect for synoptic weather forecasting. It provided the ability to track the progression of storms and provide early warning for communities that were about to be hit by severe weather.

Radar was less useful for long term weather forecasting for the simple reason that it did not produce data that could be incorporated into a numerical weather prediction model. At the time storm tracking was a largely visual exercise and radar provided a view that was unparalleled. To be of any use for weather forecasting, researchers would need to learn how to convert radar output into numbers.

The first step in this direction came in 1948, when two Canadian meteorologists showed that the echo intensity of a radar pulse—that is, the amount of the original pulse's power that was returned to the receiver—was correlated with the amount of rainfall in the next

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[183] Margaret Eileen Courain, 'Technology Reconciliation in the Remote Senseing Era of United States Civilian Weather Forecasting: 1957-1987' (Rutgers University, 1991), pp. 166–68.

[184] Courain, pp. 170–74.

hour.[185,186] Over the next decade a coherent methodology developed in the meteorological profession for converting radar images into numerical estimates of rainfall: divide the map into a grid, identify the echo intensity within each cell at each slice of time, and the sum provides a number that can be converted into an estimate of rainfall with a little math. This produced a lot of excitement among weather forecasters, as the director of climatology at the Weather Bureau explained:

> "Ever since it was shown that certain types of radar do a good job of locating precipitating clouds, there has been widespread interest in quantitative precipitation estimates. As against the known limitations of conventional rain gages, the prospect of current rainfall measurements with coverage complete both in time and space is most attractive. Enthusiasm has been high and there have been predictions that rain gages would quickly become obsolete."[187]

Unfortunately, the error was still quite high, producing estimates that were 15-30% off from the direct measurements provided by rain gages.[188] That may have been an acceptable tradeoff if radar allowed forecasters to estimate rainfall beforehand, since rain

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[185] J.S. Marshall and W. McK. Palmer, 'The Distribution of Raindrops with Size', *Journal of the Atmospheric Sciences*, 5.4 (1948), 165–66 <https://doi.org/10.1175/1520-0469(1948)005<0165:TDORWS>2.0.CO;2>.

[186] J.S. Marshall the lead author was one of the previously mentioned researchers who had noticed that rainfall was causing interference with radar during WW2. At the time he had been doing research for the Canadian National Research Council in support the war. Late in the war he was placed in charge of the Stormy Weather Group in the Canadian Army Operational Research Group, where he began work on this project. See Rod R. Rogers, 'John Stewart Marshall 1911-1992', *Bulletin of the American Meteorological Society*, 73.9 (1992), 1465–66.

[187] Landsberg, *Climatological Service Memorandum No. 98*.

[188] Landsberg, *Climatological Service Memorandum No. 98*.

gages are only useful after the rain has already fallen. But the process of retrieving echo intensity was labor intensive and would not be automated until the mid-1960s.[189]

This did not stop government from developing new radar systems from time to time and deploying them across the country. In 1957, for instance, the WSR-57 radar system was developed under contract from the Weather Bureau. Over the next 15 years the radar network would expand to 66 radar units spread across the country, though even that produced very little overlap, leading to gaps in coverage when one of the radars needed to be shut down temporarily for regular upkeep. As this became a regular occurrence the government invested in developing an updated radar system, the WSR-74, which emerged in 1973 and was installed alongside the existing WSR-57 network in an attempt to provide robustness in case one of the original radar units needed to be shut off.

Automatic quantification of radar data was finally achieved over the 1960s thanks to a series of advances that involved attaching computers to radar receivers. The foundational innovation was the Storm Radar Data Processor, or STRADAP, a specialized computer that averaged the echo intensity readings from radar output.[190] In so doing it addressed one of the main outstanding issues when it came to converting radar images to numbers. Because of the way radar collects data, that is, by sending out repeated pulses as it rotates in place, a single radar sweep produces several readings over the same space. The original

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[189] Atlas.

[190] Wilbur H. Paulsen, 'A Radar Data Processor', in *Proceedings of the Eighth Weather Radar Conference* (Boston: American Meteorological Society, 1960), pp. 335–38; Hugh J. Sweeney, 'The Weather Radar Processor', in *Proceedings of the Ninth Weather Radar Conference* (Boston: American Meteorological Society, 1961), pp. 373–78; David Atlas and others, 'Automatic Digital Radar Reflectivity Analysis of a Tornadic Storm', *Journal of Applied Meteorology and Climatology*, 2.5 (1963), 574–81 <https://doi.org/10.1175/1520-0450(1963)002<0574:ADRRAO>2.0.CO;2>.

operational experiments for STRADAP in 1962 estimated that for every degree of the circle that a radar unit covers as it turns, it takes somewhere between 4 to 8 readings. This meant that in a grid where each box was one degree wide and one nautical mile long, there were between 96 and 192 independent echo intensity readings in a single pass.[191] To make matters worse, these readings were not always the same and could even be startlingly different from one pulse to the next. This made it very complex to estimate echo intensity by hand.

The idea behind STRADAP was to use basic statistics to produce an average of these readings, knowing that the potential error in the estimate was small enough to not be problematic from a forecasting standpoint. STRADAP's automated process gave operators both a numerical representation of the echo intensity in each grid point in the radar's circular coverage area, and the height within each vertical column where the echo intensity was highest, which incidentally is also where the core of a thunderstorm is found.

By 1968 a similar technique was embedded within less expensive electronics and looped back to the standard radar display so that it could benefit visual forecasting techniques in addition to numerical ones.[192] Before the year was out, the Weather Bureau had already began adding the technology to the WSR-57 radar units it had been installing across the country over the previous few years.[193] It took nearly twenty years after the original paper

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[191] Atlas and others, p. 574.

[192] Kenneth H. Shreeve and Robert J. Erdahl, 'A Weather Radar Video Integrator and Processor', *IEEE Transactions on Geoscience Electronics*, 6.3 (1968), 152–55.

[193] Whiton and others, p. 226.

on the correlation between radar echo intensity and rainfall, but the Weather Bureau had an operational radar system that provided numerical data.

It would take another thirty years for that data to be incorporated into numerical weather prediction, for the simple reason that weather balloons already provided very similar data, near the relevant grid points in forecasting models.[194] It was not until the 1990s that grid sizes shrank to a small enough size as to require radar data to fill in the gaps between weather balloon stations.

Radar makes for a striking contrast with weather balloons, punch cards and computers on the one hand, and satellites on the other. Investing in developing and deploying radar systems had a direct impact in motivating research around how best to use the new technology. In an important sense, the friction that radar introduced to numerical weather forecasting drove innovation as researchers tried to bridge the gap between images and numbers. But while that was true, the resulting innovation did not bring radar any closer to being incorporated into forecast models, since they did not add much compared to what weather balloons already provided.

What's more, meteorologists still produced their own spontaneous order. Storm tracking already relied heavily on visual analysis to issue local short-range weather forecasts and emergency weather alerts. It was a small leap from synoptic weather charts to radar displays. As a result, the question of whether radar was worthwhile investment becomes

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[194] Bruce Macpherson and others, 'Assimilation of Radar Data in Numerical Weather Prediction (NWP) Models', in *Weather Radar: Principles and Advanced Applications* (New York: Springer, 2004), pp. 255–79.

moot. In its first few decades, radar may not have contributed much to the government's long-term goals for numerical weather prediction, but it more covered the costs of the investment in lives and property saved from extreme weather events, and researchers followed suit, investing their time and energy into further developing the technology for synoptic use.

What's also interesting is that the precise reason why radar failed to gain traction for so long in numerical weather prediction was the same thing that made it a success in storm tracking. Namely, the fact that radar produced visual data meant that it was hard to use with numerical weather prediction, but also meant that it was easy to use alongside the other visual storm tracking techniques.

Satellites

This marks and interesting point of departure for the final section of this chapter. Like radar, satellites provided images as their main data. But the images radar produced were more useful, since they probed the potential for dangerous storms, while satellites largely documented cloud cover. The limitations this posed for satellites were not immediately obvious.

Here, for instance, is the opening salvo from the interim report filed in 1959 by the ad hoc Committee on Meteorological Aspects of Satellites at the National Academy of Sciences:

> "With each advance in aerial observation from manned balloons to kits to airplanes to balloon-borne radiosonde, the horizons of the meteorologist expanded vertically, higher and higher. The advent of the large rocket succeeded in furnishing information about the important top 1% of the atmospheric mass—too high to be

> reached by balloon. However, the marked upward thrust of sounding techniques, has not been accompanied by a similar expansion laterally of meteorological observing instruments, especially over the vast island-free oceanic areas, except along the principal airplane and shipping routes. Less than 1/5 the total atmospheric mass is adequately probed by conventional meteorological sounding techniques today and large storms can reside undetected for days in many desert, polar and oceanic areas."[195]

As the authors noted in the report, satellites were never intended to replace the more finely tuned devices that already existed, like radiosondes. Instead, the primary advantage of collecting data from space was that it would provide truly global coverage.

The report understates how important global coverage really was. Weather balloons were the mainstay data source for numerical weather prediction, but weather balloons had a few crucial limitations. In the first place, weather balloons needed to be launched by a person. This meant, as I explained earlier, that it became increasingly difficult to launch weather balloons the further one got from urban centers. Nor was the problem just the far upper reaches of Alaska or deserted parts of Middle America. Two-thirds of the atmosphere sits above open ocean, where there are no people at all to launch weather balloons, except for the occasional freighter, and they could not be relied upon to launch balloons from specific points at specific times. Less impactful but no less true was the fact that aside from wealthy countries in Europe, the settler societies they left behind in North America and Oceania, and a few rich economies in East Asia, very few governments could afford the cost of

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[195] Space Science Board, *Interim Report on Satellites and Meteorology* (Washington, D.C., 1959), p. 1.

funding a weather balloon network. Weather balloons only provided data over a fraction of the global atmosphere.

Satellites held the potential to address the shortcomings of weather balloons. They could make observations over the oceans and over land regardless of how wealthy the country below happened to be.[196] Additionally, it seemed like it might be possible for satellites to make observations in layers of the atmosphere that were still too high for weather balloons to reach. This had already been an area of longstanding concern. Nearly as soon as the Second World War finished—and as Operation Paperclip imported V-2 rocket experts from Germany—the Naval Research Laboratory and the Applied Physics Laboratory at Johns Hopkins University began experimenting with using rockets to sound the upper atmosphere.[197]

The Weather Bureau recognized the value of satellites early on. In 1958 Congress held hearings on astronautics and space exploration, and called Reichelderfer, the Chief of the Weather Bureau to testify.[198] He explained that satellites held immense potential for storm tracking, since:

> "By use of photographs taken from the satellite, it will be possible to get up-to-the-minute reports, or up-to-the-hour reports, of the development of storms at sea, their

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[196] Agee.

[197] One very nice introduction to atmospheric rocket research comes in Angelina Long Callahan, 'Satellite Meteorology In The Cold War Era: Scientific Coalitions And International Leadership 1946-1964' (Georgia Institute of Technology, 2013), chap. 2.

[198] Eighty-Fifth Congress, *Hearings before the Select Committee on Astronautics and Space Exploration, H.R. 11881* (Washington, D.C.: U.S. Government Printing Office, 1958).

> movement toward the coast, and in this manner give much more definite information as to when they will strike, what their intensity will be, how large they will be, and how long they will last, and other information of that kind that is vital not only for the protection of property and for the protection of life but also to avoid the very great expenses that are connected with preparations in marginal areas where the storm doesn't strike."[199]

But he also emphasized that there was "a still more fundamental meteorological measurement"[200] that satellites would be useful for, namely, measuring the planet's energy budget by tracking the incoming radiation from the sun as well as the outgoing radiation from the earth. The benefit of this use came in two parts.

First, it could provide better insight into whether the planet was warming simply because of solar radiation. Meteorologists in the early 1950s had identified that the atmosphere was warming—some of the first climate change observations—and within just the previous year the Weather Bureau provided Charles Keeling with funding to collect measurements of atmospheric CO_2 concentrations in Hawaii to work out whether it was being driven by human activity. Incidentally, this resulted in the well-known "Keeling curve" of global warming, one of the best and earliest records of human caused climate change.

The second benefit is of more direct interest to the present dissertation: knowing the balance between incoming and outcoming radiation was, as Reichelderfer explained, "of

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[199] Congress, p. 911.

[200] Congress, p. 911.

basic importance … in any mathematical approach to the general circulation of the atmosphere which determines our storms."[201] That is, satellites could provide necessary input for numerical weather prediction.

Nonetheless, the Weather Bureau also held reservations about the use of satellites for collecting meteorological data. It was a question of whether dedicated meteorological satellites would justify the expense. For how valuable weather observations were over the oceans, the Weather Bureau still did not deploy a network of meteorological ships to gather weather reports. This would be "absurd," to use Reichelderfer's characterization.[202] Satellites would require a much larger investment than even this.[203]

Weather satellites moved forward as a collaborative project—the TIROS program—between the Advanced Research Projects Agency, NASA, and the Weather Bureau. To a considerable extent the decision to launch civilian satellites was a prestige grab on the part of the United States, which believed that it could distinguish itself from the Soviet Union by contributing non-military satellites to the growing international community around

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[201] Congress, p. 913.

[202] Congress, p. 916.

[203] In the near future the Weather Bureau would be forced to pivot as it became unclear whether NASA was going to be able to launch the project in the near term. This would change again a few months later. It was a chaotic time for weather satellites. See Callahan.

meteorology.[204] The strategic value of that prestige to the country overrode any concerns about cost or practicality.[205]

The Weather Bureau was given charge of meteorological data analysis of TIROS images, which would be transmitted to data acquisition stations in Virginia and California. As with radar, TIROS found its use early on with synoptic forecasting, that is, visually interpreting weather maps to forecast the weather a few hours in the future, or one to three days in the future. Within just one year after the first TIROS satellite launched, the Weather Bureau was already forwarding relevant information to local forecasters across the United States.

Thanks to the conference proceedings at the International Meteorological Satellite Workshop, it is possible to peek inside the operations at these data acquisitions stations.[206] The Weather Bureau assigned meteorologists to each of the two data acquisition stations, so they could be in place to act on any useful data that TIROS delivered. When satellite images were received at the station, they would be immediately fed into a television screen and photographed. After 15-20 minutes, so that the film had time to develop, the meteorologist would perform an analysis of the clouds in each picture—a nephanalysis—which would be superimposed with a standard longitude and latitude grid. Their analysis would be recorded on a base map and sent by teletype to the Weather Bureau headquarters in Maryland. At the Weather Bureau, more meteorologists would examine the

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[204] cf. Adrian Howkins, 'Political Meteorology: Weather, Climate, and the Contest for Antarctic Sovereignty, 1939–1959', *History of Meteorology*, 4 (2008), 27–40 <http://www.meteohistory.org/2008historyofmeteorology4/2howkins.pdf>.

[205] Callahan.

[206] Jay S. Winston, 'The Use of TIROS Pictures in Current Synoptic Analysis', in *Proceedings of the International Meteorological Satellite Workshop* (Washington, D.C.: Government Printing Office, 1961), pp. 95–106.

work to decide whether the results were likely to be accurate enough to be worth sending to local offices. Those that were of high enough quality were sent by fax to local forecasting offices, the Air Force, and the Navy.[207] In certain cases the meteorologist at the data acquisition station would make a phone call to the Weather Bureau even before they finished their analysis to help speed up the dissemination of important information.

Government investment in satellites paid off with storm tracking, much as it did with radar. TIROS made good observations of hurricane Debbie on September 10th, 1961—incidentally the same year that Dan Rather made his famous radar report on television—and in the process discovered a new hurricane forming further southeast in the Gulf of Mexico. The hurricane, soon to be designated hurricane Esther, was the first of many hurricanes discovered by satellite. As predicted by researchers earlier, satellites were immediately useful in providing information over areas that overwise only produced sparse data.[208]

TIROS proved considerably less useful for numerical weather prediction. Like radar, satellites produced data that were hard to reconcile with numerical modeling. But where meteorologists had known since the late 1940s that radar output correlated with values of interest, there was very little background knowledge to draw on when it came to satellites. It was not clear at all how satellite data could made into something useful. In fact, climatologists at the Weather Bureau were still having trouble making use of the data from

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[207] Winston, pp. 95–96; Courain, pp. 184–86.

[208] Winston, pp. 97–98.

TIROS in 1963. The data were so fragmented that the Weather Bureau was seeking out physicists, without success, for help in cleaning up the satellite output.[209]

The difficulty in making use of satellite data for numerical weather prediction had been anticipated by meteorologists. They were a regular feature at the various interdepartmental committees that had formed around meteorological satellites, consistently pointing out that while global imagery of cloud cover was a major development for the profession, the rest of the data was of questionable use, as things stood.

Part of the problem was a question of human capital. There was not enough expertise for any agency to make good use of satellite data, as the Weather Bureau's search for physicists already hinted at. But one report in 1960 from the Committee on Atmospheric Sciences was particularly blunt about the issue:

> "There exists at the moment no organization or group in the world that is prepared to exploit fully the new wealth of information that meteorological satellites will certainly provide. Thus, the huge expenditure of scientific effort, engineering and finances in meteorological satellites may be largely wasted unless a proper organization is ready to exploit the data output of meteorological satellites for the

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[209] H.E. Landsberg, *Climatological Services Memorandum No. 102* (Washington, D.C.: Weather Bureau, 1963).

> increase of our knowledge and the construction of a sound, theoretical foundation upon which a new order of practical forecasting can be based."[210]

For as useful as meteorological satellites may be in the long term, if there were not enough researchers striving to make use of its imagery, knowledge would not accumulate as fast as the government may want it to, given the large expenditure it had made toward launching TIROS. The other part of the problem had less to do with the number of experts that could be made to work on satellite data, and more to do with the data itself. As I already mentioned, images were the main data product from TIROS, and they did not offer much insight into the fundamental parameters of numerical weather models.[211]

But government officials were undeterred. One often repeated recommendation from federal councils and committees was that satellites provided data that was so evidently valuable, that meteorology should simply expand its practices to incorporate the new data more efficiently.[212] By 1964 the political pressure to show results had started to frustrate meteorologists. Local weather reporting offices were already complaining that they did not find satellite data very useful since radiosondes already provided more data and higher quality data over the continental United States than TIROS did.[213] Storm tracking in the

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[210] National Academy of Sciences Committee on Atmospheric Sciences, 'Certain Implications of Meteorological Satellite Programs', in *Letter from John Sievers to Dr. Hugh Odishaw* (Washington, D.C.: National Academy of Sciences, 1960).

[211] One exception to this is a technique developed in the 1960s to convert storm movement across multiple satellite images into an estimate of the wind speed over the oceans. The result was only a rough estimate, and it only worked when there were storms to follow, but the technique and its output was eventually incorporated into numerical weather prediction models.

[212] Federal Council for Science and Technology, *Minutes and Record of Actions for the Meeting of August 2, 1960* (Washington, D.C., 1960).

[213] Courain, p. 197.

oceans was valuable, but it still left satellites a little bit lacking when it came to most other weather phenomena, and maybe especially in comparison to radar which had become rather useful in a short span of time.

The frustration reached to leading meteorologists as well. Jakob Bjerknes—son of Vilhelm Bjerknes, one of the turn-of-the-century innovators in numerical weather prediction, and head of the Department of Meteorology at UCLA, the leading university department in numerical weather prediction at the time—put it this way in a retrospective speech he delivered in 1964 near the end of his career:

> “Now, don't misunderstand me as being entirely anti-space. I am not. TIROS satellites were marvelous eye-openers for synoptic meteorologists myself included; and our world-monopoly on these wonderful gadgets is a source of world prestige of which we can be justifiably proud. But let us not lose our balanced view of what scientific weather forecasting really is: l) a quick compilation of data on the present state of the global atmosphere, and 2) a quick prediction of the change of that state by time-integration of our dynamic equations. Ultraviolet, visual, and infrared observations from a space platform would help to some extent under heading (1), but hardly at all under heading (2). Even in the job of compiling the present three-dimensional state of the atmosphere I would not trade our reporting weather ships against satellites on a dollar for dollar basis. To reap the benefits from modern

> numerical forecasting we do need weather ships, and more of them, particularly in the Pacific Ocean. Satellites do not make weather ships superfluous."[214]

Here Bjerknes is raising two related issues. In the first place, satellites did not provide data that was suitable for numerical weather prediction, what he refers to as the "time-integration of our dynamic equations." But the second issue is equally important. Namely, that satellites may be a bad investment, since for the same amount of money, weather ships could be commissioned to collect more useful data over the oceans, which of course was the main selling point for satellites in the first place.

Both opinions were widely held within the meteorological community. Again in 1964, the Interdepartmental Committee for Atmospheric Sciences—organized by the National Science Foundation as a coordinating body for the many federal agencies that depend on meteorological data and research—was asked to draw up a federal-wide budget for meteorological activities. This made a lot of sense since it was staffed largely by meteorologists, though they came from different government agencies and different branches of the military. The committee was given free rein to decide what should be prioritized in the budget, but only superficially. The government wanted large amounts of funding set aside of weather control research and satellites.

When Herbert Holloman, the committee's chairperson appeared before the Federal Council for Science and Technology to present the budget, he felt it necessary to add a personal note to what had been put in print, and to register his objections to the underlying

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[214] Jacob Bjerknes, 'Half-a-Century of Change in the `meteorological Scene'', *Bulletin of the American Meteorological Society*, 45 (1964), 312–15 (pp. 3–4) <http://docs.lib.noaa.gov/rescue/Bibliographies/Bjerknes/LSN3833.PDF>.

premises of the budget he had presented, noting that they "do not represent an independent ICAS assessment of the shape and dimensions of a reasonable program." He went on:

> "The precision and time scale of weather prediction (including hurricane prediction) are not limited by absence of data, and not by the absence of a theoretical base, dynamic models, or ability to handle data. A much wider network of observations concentrating on such parameters as wind, pressure and humidity data (none of which are now provided by satellite observations) is the key to improved short and long range predictions. Improved instrumentation is in turn indispensable to the establishment of such a network"[215]

This outburst was probably just rhetorical bluster on Holloman's part, since the budget line would have returned to NASA if it had been decided that meteorological satellites should not be provisioned for. Representatives from the Interdepartmental Committee for Atmospheric Sciences had also brought up the issue in earlier meetings to question whether satellites like TIROS were being designed to fit the needs of existing meteorological research.[216] The Federal Council for Science and Technology ultimately split the difference, asking NASA to work on developing satellite technology that could more easily lend itself to typical meteorological work, and asking meteorologists to make something of what satellites were already providing.

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[215] Federal Council for Science and Technology, *Minutes and Record of Actions for the Meeting of October 27, 1964* (Washington, D.C., 1964), p. 4.

[216] e.g. Technology, *Minutes and Record of Actions for the Meeting of June 23, 1964*.

Margaret Courain, who had been the Deputy Assistant Administrator for environmental satellites' Data and Information Service at the National Oceanic and Atmospheric Administration—the parent agency to the National Weather Service—argued retrospectively in 1991 that what happened in the ensuing decades was a process of "technology reconciliation."[217] Before meteorologists could make full use of satellites for numerical weather prediction, satellites needed to be redesigned so as to collect the data most relevant to meteorology.

This process started in the early 1970s, when the National Oceanic and Atmospheric Administration began work on the ITOS series of satellites, which aptly stands for the Improved TIROS.[218] Attached to ITOS-2, which was launched in 1972, was a device called a Vertical Temperature Profile Radiometer, which used the thermal radiation emanating up from the surface of the earth to infer the temperature in the atmosphere, and at different levels of the atmosphere, across the entire planet.[219] That is, it collected temperature readings like those that radiosondes already collected.

Researchers were able to immediately set about to trying to make use of this new data. The team of scientists at the National Oceanic and Atmospheric Administration collaborated with others at the Goddard Space Center, the National Meteorological Center, and scholars

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[217] Courain.

[218] It is not unreasonable to date this process to 1959, when the original research was published on how radiation measurements could be used to infer atmospheric temperatures, e.g. Lewis D. Kaplan, 'Inference of Atmospheric Structure from Remote Radiation Measurements', *Journal of the Optical Society of America*, 49.10 (1959), 1004–7 <https://doi.org/10.1364/josa.49.001004>. But given that this was before even the TIROS series launched, it seems more reasonable to pinpoint the process as beginning with the decision to launch another series of satellites.

[219] L.M. McMillin and others, *NOAA Technical Report NESS 65* (Washington, D.C., 1973).

at the University of Wisconsin—Madison, to find a solution for incorporating these data into numerical weather prediction models.[220] One of the main problems ironically turned out to be clouds. While cloud cover was the main point of interest for TIROS images, the measurements of atmospheric temperatures from ITOS were distorted by the moisture in clouds.[221] It would take some time and a few more satellite launches for this problem to be resolved, as it required that cloudy skies were sounded using different wavelengths than the ones used by ITOS.

The work done on temperature sounding from the ITOS series of satellites marked a turning point for the use of satellite data in numerical weather prediction. Once satellites were finally equipped with devices that served the needs of state-of-the-art forecasting models, improvements came quickly. Polar orbiting satellites that could deliver similar data came soon after, as did the new GOES series of satellites in the late 1970s. By this point it was even possible to use the same techniques to estimate atmospheric moisture content, providing yet another piece of data for numerical weather prediction.

Satellites were expensive technology with the potential to dramatically improve the socio-technical system around numerical weather prediction. The timing of their emergence, though, meant that satellites got caught up in the politics and prestige of Cold War science. Systems like TIROS were launched at high cost to taxpayers, but without full consideration

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[220] Courain, pp. 190–91.

[221] Sigmund Fritz, *Investigations with Satellite Data, 2: Temperature Retrievals, 2* (College Park, MD, 1977); McMillin and others, p. 3.

of the technical apparatus it needed to carry in order to be useful to meteorologists. The result was that government intervention failed in disrupting scientific research.

What's more, much as with radar, spontaneous order seemed to win the day. Synoptic weather forecasters were already well-versed in using images to make short-range weather forecasts. It was this familiarity with the data that made it possible for satellites to have an impact when they were first launched. Synoptic weather forecasting made large advances in terms of storm tracking thanks to satellites, mainly because global blind spots were reduced, and it became less common for extreme weather events like hurricanes and cyclones to catch forecasters unawares.

	Friction with Synoptic Weather Forecasting	Friction with Numerical Weather Prediction	Impact on R&D
Weather balloons	None	None	Fundamental pre-requisite for numerical weather prediction research. Availability of the system is necessary for all developments in the area.
Punch cards and computers	None	None	Amplifies the capabilities of researchers. Makes possible the fast computation of numerical weather models. Leads to explosion of research on numerical weather prediction
Radar	None	Some, resolved quickly	Expands the capability of synoptic weather forecasting by providing data on previously unobserved regions. Problems with turning images into numbers generates research into solving the issue, but the resulting data provides little benefit over existing radiosonde data.
Satellites	None	Some, resolved slowly	Expands the capability of synoptic weather forecasting by providing data on previously unobserved regions. Does not contribute to numerical weather forecasting until new satellites are launched.

Table 3: Summary of the impact of four technologies. *New technologies raised no new problems for the older visual analysis methods of synoptic weather forecasting and expanded the overall capabilities of the socio-technical system as a result. Weather balloons, punch cards and computers served as crucial developments for numerical weather prediction, enabling work to be done on to improve the socio-technical system. By contrast, radar and satellites do not initially provide useful data for numerical weather prediction, and so despite the large investments that were necessary to bring them about, radar and satellites struggle to contribute to the socio-technical system for several decades.*

Conclusion

By the mid-1970s, the weather forecasting machine had largely incorporated the major products of government investment in technology R&D. The weather balloon system continued to be the main source of data for numerical weather prediction. Techniques to convert radar images to numbers had proven successful, even if they did not yet provide an improvement over weather balloons. And new satellite systems were being launched that played into the strengths of numerical weather forecasting. There was still work to be done, but the initial problems that radar and satellites faced around getting their data incorporated into the work of numerical weather prediction was largely over. The tone in the interactions between meteorologists and government had changed as well. There were fewer complaints about spending priorities, and more calls for making it easier to access and use radar and satellite data. Readers can consult Table 3 for a quick summary of the main points in this chapter.

Chapter 2 showed that the US government had played a decisive role in building out the system for numerical weather prediction. Science had only moved forward in the way it had because of the consistent support that the government had provided. The history here has taken a closer look at how the various technologies around weather forecasting were received by the meteorological community. There was a lot of variation from technology to technology in terms of how much value they provided for researchers.

At a basic level, government intervention did not always succeed in making researchers take up projects related to numerical weather prediction. The radar network and weather satellites had very little impact on numerical weather prediction for the first ten to fifteen years of their existence. With radar the main problem was that the progress in learning how to usefully convert radar output into numbers was slow-going. Many of the basic principles had been known since the late 1940s, but the work was time consuming and did not always represent an improvement over what already existed. Rain gages still proved to be more accurate in recording rainfall and weather balloons offered a more direct measurement of atmospheric moisture levels.

Satellites had a more difficult path toward usefulness. Because the government launched TIROS in part with hopes of garnering international prestige, the first meteorological satellites did not collect any data that was of immediate use to weather forecasters. R&D continued on the ground in the meantime, but despite the sophistication and cost of the technology, satellites brought virtually no change to the socio-technical system around numerical weather prediction until new series of satellites were designed and launched in the mid-1970s.

It needs to be said that this was a short-term issue for meteorology. Much as Rosenberg and Arthur would have predicted,[222] the problems that radar and satellites posed to the field inspired research into finding solutions. In this way, innovation begat more innovation. But it also needs to be said that this was more true for radar than it was for satellites. There was only so much problem solving that could be done before new satellites were launched into orbit, themselves loaded with sounding devices that could produce

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[222] Rosenberg; Arthur, *The Nature of Technology: What It Is and How It Evolves*; cf. Dosi.

useful data. Much of TIROS was fundamentally incompatible—or irreconcilable, to use Courain's language[223]—with what numerical weather prediction was up to.

Despite the failure to spur research into numerical weather prediction with these two technologies, meteorologists still found ways to make use of the new data. This was Polanyi's spontaneous order in action, still operative despite government intervention. Researchers realized rather quickly that the images that were so problematic for numerical weather prediction were still useful for the older practice of synoptic weather forecasting.

The cases where government intervention was successful are just as instructive since their impact appears to have come more from changing the research landscape around numerical weather prediction. In just this way, despite being more low-tech than the other examples I have covered in this chapter, the weather balloon network nonetheless had a large impact. So too did computers.

First consider weather balloons. Numerical weather prediction was contingent on making observations in the upper atmosphere, something weather balloons were designed to do from their very inception. As a result, progress in weather forecasting was closely tied to improvements to the station network and weather balloon technology itself. Much of these innovations came before the Second World War, but even rawinsondes were quickly incorporated without debate into the socio-technical system during the early 1950s. Up through the 1970s, weather balloons only entered into discourse around the weather forecasting machinery when meteorologists would make calls to launch them more

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[223] Courain.

frequently or decrease the physical space between stations, as collecting more data using weather balloons remained one of the simplest ways to expand the system's capabilities.

The government's investments in mechanizing data and in digital computers had a very similar impact as they did away with the calculation problem around numerical weather prediction. Taking advantage of numerical weather prediction in the long-term always meant finding a solution to the enormous amount of human capital that it would take to run something like Richardson's forecast factory. Computers offered exactly that opportunity and government seized on it, installing state-of-the-art systems for data processing and modeling. This, of course, came in the wake of government's decision to fund the routine storage of meteorological data using punch cards to make the process of recovering data for analysis less burdensome. Forecasting models evolved alongside the available computing power each step of the way, and the larger socio-technical system did as well.

The investments made by the government in providing computer technology and an upper atmosphere observation network highlight the powerful impact that so many scholars have associated with the mid-20th century US state.[224] Cutting-edge technology was deployed in a way that suited the needs of numerical weather prediction, at a time when very few (if any) organizations other than the government could provide them. Whatever value came of weather forecasting in this period owes significantly to these government investments.

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[224] Desrosières; Michel Foucault, *The Birth of Biopolitics: Lectures at the College de France, 1978-1979* (New York: Palgrave MacMillan, 2008); Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*.

The general opinion was that there was plenty of value to be had. In preparation for the 1958 Congressional hearings on astronautics and space, for instance, the Weather Bureau reached out to its user base for estimates on how much value accurate long-range weather forecasts would have. Here is one selection from the results:

> "…the university extension service of one of the States estimates that $5 million would be added to farm income in that State alone if forecasts for a period of 5 days or so were 100 percent accurate. For farming in general, the figure that was given to me is $2 1/2 billion a year. For the lumber industry, $45 million. For transportation, exclusive of air transport, $100 million. In the very important field of water resources, the planning of how to handle water stored for irrigation, in light of what the weather will be a few days or a few weeks ahead, the estimate is $3 billion a year. Retail marketing values would be great. Certainly on the order of $50 million or $100 million per year."[225]

Weather balloons and computers represent the government at its most powerful, or at least at its most impactful, in terms of setting a direction for the accumulation of knowledge and the evolution of technology. But they were impactful not because they disrupted the spontaneous order in science. Far from it, meteorologists seemed nonplussed by government intervention and consistently searched widely for ways to apply the new technology, even when it differed from the government's original plan.

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[225] Congress, pp. 910–11.

Instead, government intervention was successful in weather forecasting—and successful in securing the massive value that the quote above testifies to—because technologies like weather balloons and computers changed the basic possibilities for scientific research. The US government had changed the landscape.

Chapter 4:

An unintentionally innovative state

Introduction

The previous chapter examined the situation around weather forecasting, where consistent government interest allowed for the analysis of the mechanisms involved in government intervention. It turned out that weather forecasting was affected more by the government's ability to shape the landscape for research than it was by any disruption in the spontaneous order of science. In-vehicle road navigation took a different path because of Congress' decision to withdraw funding. As a result, this is concerned with a different question, albeit a related one. That is, what were the consequence of the termination of research around smart highway technology?

There are two threads to follow. The first half of the chapter is concerned with the return of spontaneous order to industrial laboratories in the absence of government intervention. Research into in-vehicle road navigation may have stopped, but what I will show is that the knowledge that was produced as part of smart highway research was transferred to other countries and other applications. In fact, this process began before the government shut down its support for smart highway research, suggesting that government intervention was not disrupting the ability of researchers to search the landscape for more useful ways to use the technology. Judging from the timing, spontaneous order may not have returned to industrial laboratories. On the contrary, it may have never left.

The second half of the chapter follows the second thread, which is how in-vehicle road navigation was re-assembled by the late 1990s. Despite having withdrawn its support from the earlier iteration of the technology, the US government played a major role in developing GPS navigation. To make matters even more curious, government agencies contributed by providing fundamental technology that changed the research landscape, much as it was slated to do initially with smart highways in the 1950s and 1960s. What distinguishes the government's role in GPS navigation and smart highways is that its earlier interventions were intentional. Government agencies not only contributed unwittingly to the development of GPS navigation, but also unwillingly.

Dismantling (and relocating) smart highway research

The massive amount of funding that went toward the interstate highway system in the United States prompted the electronics and automotive industries to develop smart highway technology to help with safety and in-vehicle navigation. Chapter 2 shows how this took form in technology developed in the 1950s and 1960s like General Motors' Auto-Control and DAIR, meant respectively to provide automated vehicles and in-vehicle road navigation. When government cut funding to these programs in 1971, it seemed like smart highway technology had simply failed to take hold in the marketplace, a signal of just how much sway governments hold over the fate of large technology systems. Scholars appear to share this view, seeing this as an example of failed technology or just a curious aside to the version of intelligent transportation systems that were built around world in the 1990s.[226]

But this does not tell the whole story. Already by the early-1960s the idea of burying magnetic wire in the ground and using the electromagnetic field to automatically control vehicles, originally developed by Radio Corporation of America and General Motors Research Laboratory, had inspired researchers working in other nearby fields of research.

From the road to the yard

Landscaping and agriculture companies invested heavily in researching how to apply the same technology to their own use cases. In principle, magnetic wires buried in the ground could be used to chart a path for lawn mowers, harvesters, planters, and the like, to follow and carry out their work without much human supervision at all.

Unfortunately, researchers had not quite figured out how to make buried magnetic wires convenient for consumers. Arthur Barrett explains: "…because of the cost and physical inconvenience of disturbing the landscaping to bury the guiding conductor which must extend along the exact path to be followed by the mower in each cutting operation, such arrangements have not received general acceptance at the consumer level."[227]

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[226] e.g. Frank W. Geels and Wim A. Smit, 'Failed Technology Futures: Pitfalls and Lessons from a Historical Survey', *Futures*, 32 (2000), 867–85 <https://doi.org/10.1016/S0016-3287(00)00036-7>; Joseph M. Sussman, 'ITS: A Short History and Perspective on the Future', *Transportation Quarterly*, 50.4 (1996), 115–25 <https://doi.org/10.1007/0-387-23260-5_1>; Hans Klein, 'Technology Push-over: Defense Downturns and Civilian Technology Policy', *Research Policy*, 30.6 (2001), 937–51 <https://doi.org/10.1016/S0048-7333(00)00166-9>.

[227] Arthur M. Barrett Jr., 'Random Control for Power-Driven Unit' (USA, 1962), p. 1.

This quote comes from a patent that the Barrett Electronics Corporation filed in 1962 for a “random control” system. Barrett’s idea was to use the magnetic wires to define a boundary for vehicles to stay within and allow the vehicles themselves to bounce around the space to cover the entire space and avoid repeating the same diamond pattern. Except in unique circumstances, the lawnmower (or whatever else) would eventually cover the entire space within the magnetically defined boundary. There were a number of patents filed in the 1960s with similar ideas for lawncare and agriculture. This is visible in Figure 2, which shows the number of patent filings around magnetic wire technology in three domains: soil working in agriculture or forestry, harvesting or mowing, and motor vehicles or trailers.

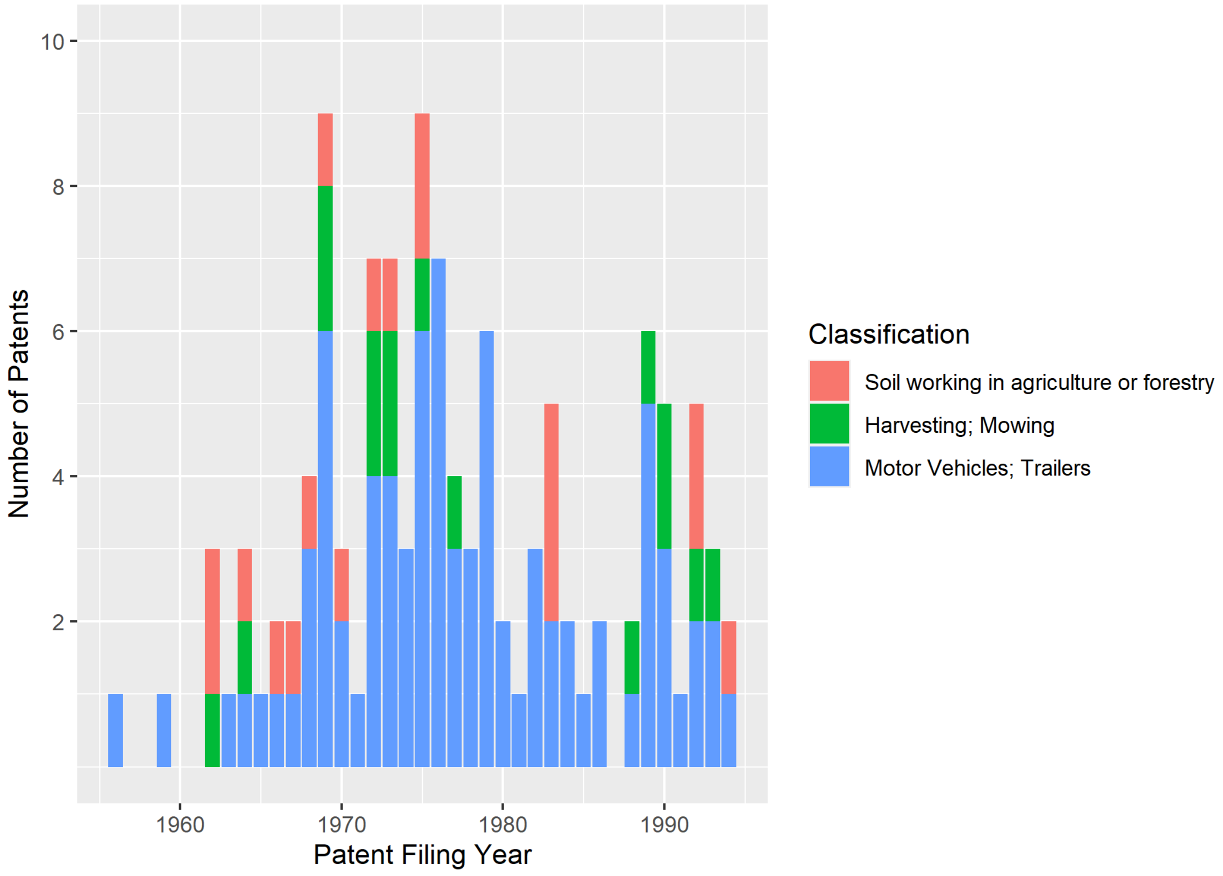

Figure 2: USPTO patent filings by three subclassifications over time from 1950 to 1995. *While smart highway research in the US is effectively ended in 1971 with Congress' decision to not provide any further funding, that same decision has no discernible effect on patent filings around the same technology in adjacent research domains. The decade from the late 1960s to the late 1970s actually represents the high point in patent filings in these domains. Subclassifications here are CPC subclasses A01B (soil working in agriculture or forestry), A01D (harvesting; mowing), and B62D (motor vehicles; tractors). The counts represent the number patents that were filed in year "t" within CPC classification G05D1/0265 (vehicle control of motor vehicles using buried wires), which are also classified using the three focal subclasses. Data was collected using Google Patents, and subsequently merged with patent metadata from USTPO PatentsView.*

By 1969 automatic mowers that used much of the same technology as General Motors' failed Auto-Control system were available for order. The following is a snippet from a story in *Popular Science* about the new "Mowbot" that you could buy for $800:

> "It seems like magic, the way the Mowbot turns away from obstructions, runs up to a flower bed and thoughtfully makes a swing to left or right without mangling a single marigold, mows circles around midyard trees, and stops instantly if it bumps into anything solid—like your ankle. It's not magic. It's electronics."[228]

Seemingly far away from the original reason companies became interested in magnetic wire technology—the construction of the interstate highway system—the technology found another place to flourish, even as the government contemplated retiring its research projects at the Bureau of Public Roads. As you can also see from Figure 2, the same magnetic wire technology made a return in the mid-2000s thanks to new machines from Husqvarna, John Deere, and Caterpillar.

It was not just mowing and farming that was impacted by these technology transfers. Warehouses and factories adopted the technology just as quickly. Five years after RCA's initial patent around automatic vehicle control, General Mills filed a patent of its own that aimed to apply the same technology to complex warehouse situations where vehicles with different tasks may end up crossing each other at intersections, necessitating an additional layer of control in comparison to the automatic highway technology that assumed traffic

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[228] Jackson Hand, 'New Robot Lawn Mower Works While You Rest: Electronics Keeps Automatic Machine within Limits as It Cuts Your Grass in Random Crisscross', *Popular Science* (New York, 1969), pp. 136–38, 210 (pp. 136–37).

was flowing in a single direction.[229] Work in this area actually peaked around the same time that the US government withdrew funding from road navigation systems, and continued for decades after that.

While the government may have unilaterally chosen to end research on smart highways that took advantage of magnetic wires in the road, the innovation it helped incentivize survived and continued to be productive with only a short leap to agriculture and warehousing. The US government's intervention into smart highway technology certainly influenced the choice of research topics by industrial laboratories like those at General Motors. This is clear from the virtual disappearance of smart highway research after 1971. But science crosses the boundaries of disciplines and industries, making it harder for governments to disrupt Polanyi's "spontaneous order." When the government affected the type of research that was being done in the motor vehicle industry, that did nothing to disrupt the search process for everyone else, even with the very same technology.

Smart highways go international

Government intervention only disrupted scientific research at specific laboratories. But there is an even more basic limitation: it only disrupted scientific research in the United States. This was about to change. Japan and Germany each launched research projects around the technology in the 1970s, in time for their own highway network expansions.[230]

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[229] Charles Francis Faluka, 'Device for Automatic Steering of a Vehicle' (USA, 1958).

[230] The best research on the diffusion of smart highway technologies around the globe is Hans Klein's unpublished dissertation. Hans K. Klein. While I am indebted to his work on the public sector research, Klein's account does not provide a substantial consideration of the private sector's contributions. The patterns in patenting that I show here suggest that the line of research that was taken up in Japan and Germany was far more extensive than Klein was able to document with only the research material from each country's government labs.

Figure 3 shows just how comprehensively the research trajectory around smart highways moved from country to country as different governments showed interest. After doing virtually no research into the magnetic wire technology for smart highways in the 1960s, Japan and Germany become innovation leaders in the domain starting in the early 1970s as each country considers building their own smart highways systems.

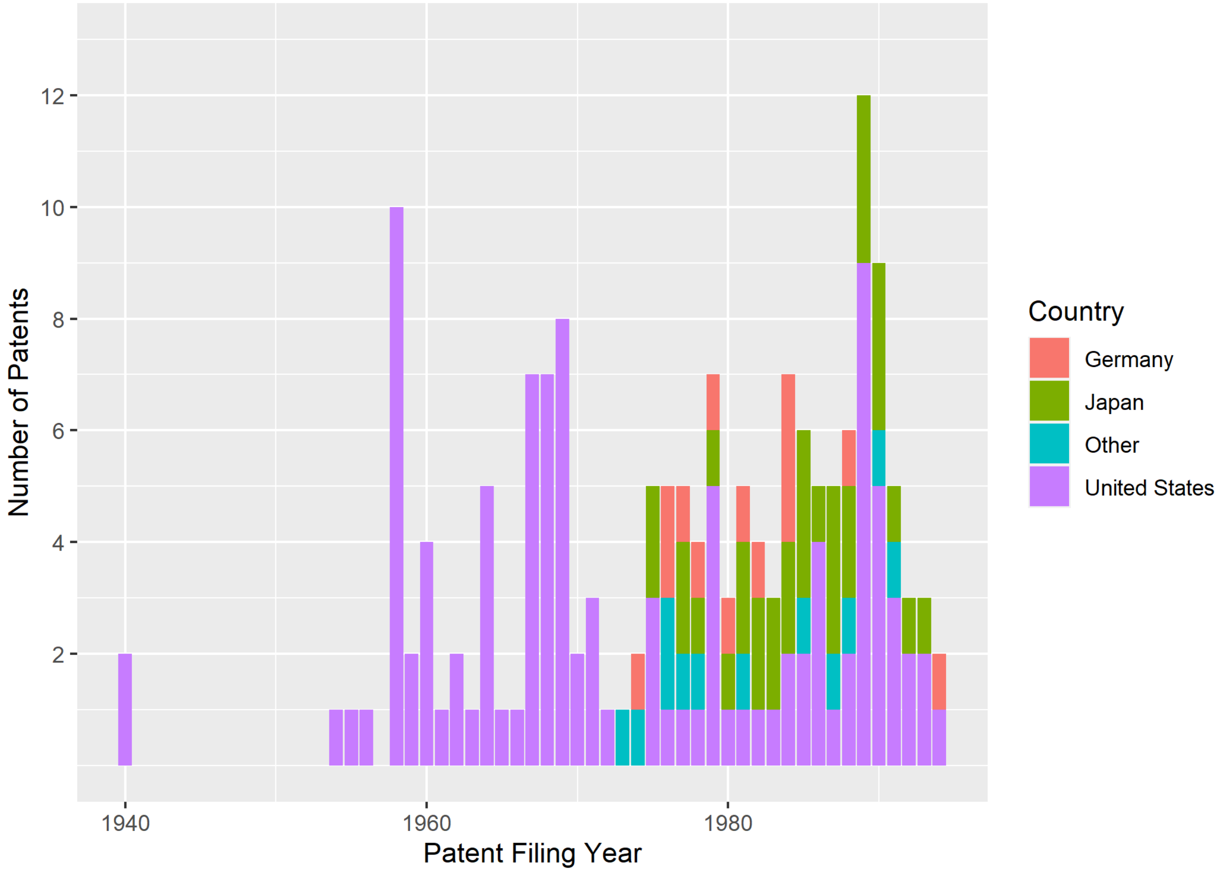

Figure 3: USPTO patent filings per year in CPC classification G05D1/0265 (vehicle control of motor vehicles using buried wires) across four different countries from 1940 to 1995. *After the 1971 decision from Congress to provide no further funding to smart highway research, research in the United States slows down dramatically. Despite the clear impact felt in the United States, starting in the early 1970s patent filings for the same technology take off in Germany and Japan, as each country considers their own smart highway systems. Data was collected using Google Patents, and subsequently merged with patent metadata from USTPO PatentsView for patents filed on or after Jan. 1, 1976, and with patent metadata from HistPat[231] for patents filed on or before Dec. 31, 1975. A small number of patents are not included in the chart because their location data remains irretrievable across both metadata collections.*

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[231] Sergio Petralia, Pierre Alexandre Balland, and David L. Rigby, 'Unveiling the Geography of Historical Patents in the United States from 1836 to 1975', *Scientific Data*, 3 (2016), 1–14 <https://doi.org/10.1038/sdata.2016.74>.

The Ministry of Trade and Industry—whose role in spurring economic development in Japan has been documented elsewhere[232]—took the lead in the project in Japan, organizing research in companies like Toyota, Sumimoto Electric, Hitachi, and Honda. The result was what they called the Comprehensive Automobile Traffic Control System (CACS). While at the core CACS resembled the US Bureau of Public Roads' ERGS in having roadside computers and buried magnetic wires, everything was scaled up.

Rather than build out the technology with highways in mind, as they did in the United States, CACS was tested out in an area covering 28 square kilometers in Tokyo, increasing both the scale of the system and the technical challenges in finding the shortest route. Even more substantial was the decision to share some of the computational burden between the roadside computers and the in-vehicle receiver.[233] Japan was already positioning itself to shake up the small electronics market and this fit nicely with that overall industrial strategy.

Scaling up the technology brought problems. As I hinted a moment ago, the basic task of computing the shortest route becomes considerably harder as the road network becomes larger and denser. To deal with this the engineers developed a technique for approximating the road network so that the set of roads included in the calculation are more comprehensive near a traveler's origin point and increasingly simplified, with extraneous details removed, further away from the origin point. This meant that some of the routes

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[232] See especially Peter Evans; Johnson.

[233] Nobuo Yumoto and others, 'Outline of the Comprehensive Automobile Traffic Control Pilot Test System', *Transportation Research Board*, 737 (1979), 113–21.

that CACS recommended were slightly less than optimal, but they would be close enough to be worth the trade-off in computation time.

More problematic was the decision to split those computations across the roadside computer and the in-vehicle receiver. This meant that the technology would only be useable once motorists had the receivers in their cars. As the Nebraska Highway Authority had experienced in the United States with General Motors' Auto-Control system, Japanese governments at all levels were faced with a chicken-and-egg problem. Consumers had no reason to buy receivers until the infrastructure was in place, but governments had little incentive to build the infrastructure without knowing that there were enough receivers on the road to make the investment worthwhile.[234] This issue was not solved until the late 1980s, when Japan was testing out the successor technology to CACS. Industry took on the burden of aggressively marketing and selling in-vehicle receivers before the infrastructure was put in place by the government. They were relatively successful at it, too, selling around 500,000 units by 1993.[235] Of course, by then GPS navigation was just beginning to emerge, rendering all that effort moot.

At nearly the same moment when Japan was started to develop CACS, Germany began working on its own system that it called ALI (Route Guidance and Information System), a partnership between the Federal Ministry of Traffic and the electronics and automotive sector, though Siemens and Bosch took the leading roles.[236] Bosch's involvement in

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[234] Hans K. Klein, p. 125.

[235] Hans K. Klein, p. 140.

[236] Hans K. Klein, pp. 157–60.

particular is interesting since it was one of the leading companies in developing magnetic wire technologies for warehouse applications, allowing it to take advantage of the in-house expertise it had built up and apply it toward the original use case that General Motors had dreamt of over the previous two decades.

ALI, like CACS in Japan, imitated the ERGS from the US Bureau of Public Roads in most respects. It even focused on the autobahn network rather than the urban road network. But as you can infer from the volume of research from Germany shown in Figure 3, Germany pushed the technology still further.[237] The most unique contribution coming out of the research into ALI was its ambition to optimize the route guidance based on the local traffic situation. Techniques were developed to not only use the magnetic wire to communicate with passing vehicles, but to calculate the speed at which vehicles were passing, and the volume of traffic on the road. These factors could then be loaded into the network model and used to compute the shortest route, given the current traffic conditions.

ALI was eventually subsumed into a larger pan-European program called PROMETHEUS that aimed to not just provide information to motorists but actively control and manage the traffic system across the European road network. At that point it becomes more difficult to track the influence of the original smart highway research, as the “intelligent transportation systems” that developed starting in the late 1980s aimed to provide a much wider array of services to motorists.

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[237] Peter Braegas, ‘Function, Equipment, and Field Testing of a Route Guidance and Information System for Drivers (ALI)’, *IEEE Transactions on Vehicular Technology*, 29.2 (1980), 216–25 <https://doi.org/10.1109/T-VT.1980.23843>.

What is clear from the way research moved from country to country is that the nature of smart highways made it so that the government provided first-order selection for research, something I noted in Chapter 2.[238] Industrial laboratories, and in many cases university researchers as well, will not invest their effort into researching a topic unless there is some assurance that potential buyers really exist. All of the smart highway projects considered here launched after governments indicated that they were expanding the national highway system. On the other end, research petered out when governments stopped funding it.

The diffusion of knowledge across border highlights another challenge for government intervention. From the perspective of the global economy, the ease with which smart highway research made its way from the United States to Japan and Germany underscores that the single-buyer markets that seem to exist around large-scale technologies (i.e., where the government is the only viable buyer) are more complex when seen at the international level. Any government willing to subsidize research or indicate interest around a given technology can spur R&D in the private sector. This means that while governments have an impressive ability to shut down specific research by withdrawing funding or interest, it may not matter for the long-term accumulation of knowledge and the evolution of technology.

Where things become more complicated is interpreting these results from the perspective of national competitive advantage. Countries can and do try to outmaneuver each other in

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[238] Dosi.

becoming the main supplier for key technologies worldwide. To the extent that one of these large-scale technologies is of vital importance in that competition, it is problematic that withdrawing research funding only stalls the accumulation of knowledge at home, without affecting it abroad. States may undermine their own competitive advantage in taking these actions.

One thing that does not depend on your perspective on political economy is that ideas and technology can still migrate from one industry to another even without government support. This is something of a corollary to Arrow's work on market failures for innovation.[239] Arrow demonstrated that because one company's innovations can be imitated by its competitors, markets on their own provide little incentive to invest resources toward R&D. Historically, the main solution to this market failure has been the patent system, which guarantees inventors and the firms they represent exclusive rights to the innovations they produce.

Governments are limited by something very similar. Because innovations can be adopted rather freely by other industries, the risk that governments run of shutting down research around certain ideas by withdrawing funding is muted by the way ideas can still be picked up and used in R&D that is less dependent on government funding.

Innovating in-vehicle road navigation for the 21st century

So much for the "failed" in-vehicle road navigation technology from the 1950s and the 1960s. The technology that emerged in the late 1990s was different. It required less

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[239] Arrow.

infrastructure and more personal electronics. But despite this difference, the government was no less involved. After all, the road maps that Mapquest, Navtek, TeleAtlas, and eventually also Google, all used in their mobile device were based on government road maps that had been compiled in the decades since smart highway research was defunded. The Global Positioning System, of course, is military technology and itself a product of government intervention.

The three subsections below trace the development of the GPS in-vehicle road navigation technology that readers are likely familiar with from their everyday lives. An odd pattern emerges in the history. While government impacted the development of these technologies more by changing the research landscape than by disrupting the spontaneous order in science, just as it did with the weather forecasting research I covered in Chapter 3, here the government never intended to create in-vehicle navigation for the 21st century. If the government was innovative, it was unintentionally innovative.

Transit and the origins of satellite navigation

At the same time as the US government was developing smart highway technology, work had already begun on satellite navigation, though it was targeted very specifically for military use. By the time smart highway research was defunded, satellites were poised to provide navigation services of their own. It is easy to forget since most people spend the bulk of their time on land, but satellite navigation in the open sea and in the air have been operative since the 1970s.

The story of satellite navigation begins, rather curiously, with Ph.D. student George Weiffenbach, who was working at the Applied Physics Laboratory at Johns Hopkins

University. Weiffenbach's research was not about satellites at all, but experimental molecular physics. Like in many other intellectual histories, innovation came serendipitously. The crucial details: Weiffenbach was using a microwave spectroscope in his project, and the Soviet Union had just launched Sputnik. This is how he explained it:

> "Part of my apparatus was a Collins receiver tuned to the WWV time and frequency transmissions at 20 MHz to monitor the microwave spectrometer's frequency standard. When the news broke on 4 October 1957 that Russia had launched a satellite and that it was transmitting at 20 MHz it was natural to tune Sputnik in on the Collins. Bill Guier and I did just that—and there was Sputnik coming in loud and clear."
>
> "Our first bit of luck was the Russians' choice of frequency—just above WWV—so that the beat note between the satellite signal and WWV was clearly audible. We could hear the distinctive beeping as the satellite signal was switched on and off. We were convinced that the beeping was some form of telemetry, and tried—unsuccessfully—to discern some pattern. After about a week the beeping stopped, but the satellite continued transmitting a continuous frequency. After listening to all the passes that first week it was apparent that the Doppler shift was also a distinctive and reliable signature for Sputnik. There was no mistaking the satellite signal, even in the congested 20 MHz band with the receiver bandwidth opened wide to accommodate the full swing of the Doppler frequency."[240]

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[240] George C. Weiffenbach, 'The Genesis of Transit', *IEEE Transactions on Aerospace and Electronic Systems*, 22.4 (1986), 474–81 (p. 474) <https://doi.org/10.1109/TAES.1986.310791>.

Readers are probably familiar with the Doppler shift, at least in its everyday effects. The Doppler shift is why police and fire sirens (or car engines) seem to have a higher pitch when the vehicle is coming toward you, and a lower pitch when it is driving away. The principle applies to electromagnetic waves as well, like the ones that Sputnik used to communicate with the surface. What Weiffenbach and Guier came to realize was that they could track Sputnik by listening for how its waves were affected by the Doppler effect, almost as if the satellite were another police car driving by. Their results were ultimately published by *Nature* in 1958.[241]

This coincided with a problem at the US Navy. American submarines at the time navigated using automated systems that tracked the vessels' inertia, making an informed estimate of where they were now given where they started and how their momentum changed over time. But these systems were also vulnerable to accumulating small errors over time unless they were recalibrated with the "true" location at regular intervals. Today the cell phone you carry in your pocket or the smartwatch you wear on your wrist recalibrate their inertial systems by checking in with GPS location estimates. In the late 1950s this was not an option.

Weiffenbach's and Guier's colleagues at the Applied Physics Laboratory were not only aware of their work on tracking satellites but had been looped in on the challenges that submarines were facing in navigating using inertial systems. They recognized that the Doppler shift calculations used in solving for the orbits of satellites could be reversed with

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[241] William H. Guier and George C. Weiffenbach, 'Theoretical Analysis of Doppler Radio Signals from Earth Satellites', *Nature*, 4622 (1958), 1525–26 <https://doi.org/https://doi.org/10.1038/1811525a0>.

a little work to find the position of the observer on the ground if the position of the satellite was already known. Along with the funding and coordination provided by the federal government's Advanced Research Projects Agency,[242] this marked the inception of the Transit navigation system.

The first Transit satellite was launched in late 1959, and while it unfortunately failed to gain orbit and crashed into the Atlantic Ocean off Ireland, the short flight was still long enough for the Doppler shift to provide position information at two different locations. The results were promising enough that over the next two years a series of follow-up experiments were run to help make an operational Transit system viable.

This is not to say that there were no more stumbles. One of these experiments happened on November 30th, 1960. The satellite launch once again failed and crashed, this time on a cow in Cuba, prompting a mild international incident and student protests in Havana.[243] But by the end of 1962 the system was accomplishing its design objectives and by the end of 1964 ballistic missile submarines in the US fleet were using the Doppler shift from overhead Transit satellites to find their location on the planet and recalibrate their inertial systems.

In 1967 President Johnson announced that satellite navigation using Transit would be made available to the general public. But it appears that the main user base was imagined to be seafarers, and that no serious consideration was given to using the system in motor

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[242] The Advanced Research Projects Agency would eventually become the Defense Advanced Research Projects Agency, or DARPA.

[243] R. Hart Phillip, 'Cubans and Cows March in Protest; 300 Havana Students Mourn Beast Killed by Pieces of U.S. Space Rocket', *The New York Times* (New York, 5 December 1960), p. 12.

vehicles on land. Vice President Humphrey was rather explicit about this in a speech he delivered to oceanographers at Bowdoin College in late 1967:

> "This week the President approved a recommendation from the council, from the marine council, that the Navy's navigation satellite system be made available for use by our civilian ships and that the commercial manufacture of the required shipboard receivers be encouraged. … Our all-weather satellite system has been in use since 1964 by the United States Navy and it has enabled our fleet units to pinpoint their positions anywhere on earth. The same degree of navigational accuracy will now be available to our non-military ships as of today. For the past year there has been an increasing interest in this system in the entire oceanographic community. Some of you undoubtedly have communicated with your members of congress. There's been great interest amongst offshore oil exploration companies, amongst mineral companies and among other segments of U.S. industry which require extremely accurate navigation or position. The old system just wasn't that good. These users will now have the best that modern science and technology can provide, and they will be direct beneficiaries of this new dividend from our military research and our development programs. I can tell you that we're doing the same thing in the space program today. Where we're literally spinning off into the civilian economy, hundreds of new developments that are literally going to make well, I was going to say revolutionize American industry, but let me tell you make the degree of excellence in American industry, greater and greater. One of the most thrilling experiences of my life is to see what happens in this field of science and technology, that where we put in billions of dollars of federal government resources in a

> program like space for example, or millions of dollars like we do in oceanography and see what comes out of it in terms of human benefits, not just defense, not just military security, but human security and human benefits."[244]

Now, it is entirely possible that Humphrey was simply playing to his oceanographic audience in highlighting that the navigation system would be used by civilian ships, but Magnavox—the main supplier of user-side receivers for the Transit system—indicated the same thing about the user base just 15 years later. In an information piece put together for potential buyers, Magnavox described 11 known use cases for their Transit equipment, ranging from shipping freighters and private yachts to oil exploration vessels and drifting buoys.[245] Only one was land based, and it was for surveying, not navigation.

The main issue seems to have been cost. Satellite systems like Transit were largely "passive" in the sense that users did not need to supply any information to the satellites in order to receive their location. But this also meant that on-board computers were unnecessary. Whatever calculations needed to be done could be completed by on the user's side. With in-vehicle road navigation this was a decisive difference compared to the roadside computers that made smart highway technology viable. With DAIR from General Motors or ERGS from the Bureau of Public Roads, roadside computers played a similar role to the satellites, providing information a receiver in the vehicle. But they also handled the storage of digital road maps and processed the algorithm for calculating the shortest route.

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[244] Hubert Humphrey, 'Address to the Oceanographic Institute, July 29 1967, Bowdoin College' (Minnesota Historical Society, Hubert H. Humphery Papers, 1967), S.16.H Box 28, 5-6.

[245] Thomas A Stansell, *The Transit Navigation Satellite System*, 1983.

The receiver in the vehicle simply had to relay that information to the driver. With no computer embedded into the orbiting satellites, Transit forced all the necessary data storage and computation onto the user's receiver. From the 1960s all the way through the 1980s, the small electronics that could provide that amount of storage and computation were very expensive.

One way to conceptualize just how expensive these devices would have been is to look at the prices that satellite navigation companies charged for their nautical navigation devices. Hobbyist magazines give an easy window into this issue. The earliest price-point I could find for civilian Transit receivers is from 1970, from *Motorboating* magazine, which cited a "rather high" price of $65,000 for a single receiver.[246] By 1977 the price had dropped considerably, with Magnavox selling top-of-the-line receivers for $25,000 and Navidyne selling a budget-priced version for just $15,000.[247] It took until 1981 just for the price to drop beneath $5000.[248] These prices may not reflect exactly what it have cost to purchase these systems for a car, but note that for the average consumer, buying a satellite navigation receiver would have cost nearly as much as a brand new car. By 1981 the Ford Mustang was selling at a price of $7000.

Despite the prohibitive costs for users, automakers never truly gave up on the dream of providing in-vehicle navigation. Land navigation technology simply fell behind the technology for sea and air navigation. In 1981 Honda, perhaps frustrated with Japan's

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[246] Conrad Miller, 'Doppler: New Heart of Electronic Navigation', *Motorboating* (New York, September 1970), pp. 76–78.

[247] Manfred Meisels, 'Push Button to Tahiti', *Motorboating* (New York, June 1977), pp. 18–19, 32.

[248] Staff, 'What's New in Electronics', *Motorboating* (New York, June 1981), p. 94.

failure to deploy the CACS smart highway technology, launched an inertial navigation system that it called the Electro Gyrocator. This was effectively same technology that US submarines were using to navigate in the 1950s before Transit was developed, only it linked to an in-vehicle CRT display that would show the vehicle's position on a digital map. In its technical paper on the topic, Honda noted that this was less than ideal, and far from the cutting-edge. Nevertheless, it argued, the Electro Gyrocator was bound to be useful since government acquisition of neither the magnetic wire technology nor satellite receiver technology seemed imminent.[249] In fact, it was promising enough that the US Army Missile Laboratory studied the system to see if the military could make use of it. The lab report concluded that Honda's device was not accurate enough for military uses, but that it should be a fine addition to the consumer market.[250]

Work continued in North America too. In 1983, Ford—which, recall from Chapter 2, was one of the companies contracted with developing ERGS for the US government—unveiled a concept car that used Transit along with an on-board inertial system to determine its location in the road network.[251] A CRT display in the dash marked a digital map with your location and heading. This technology was never brought to market.

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[249] Katsutoshi Tagami, Tsuneo Takahashi, and Fumitaka Takahashi, '"Electro Gyro-Cator" New Inertial Navigation System for Use in Automobiles', *SAE Technical Papers*, 92.1983 (1983), 1103–14 <https://doi.org/10.4271/830659>; cf. Masayuki Arai, Yukinobu Nakamura, and Isao Shirakawa, 'History of Development of Map-Based Automotive Navigation System "Honda Electro Gyrocator"', in *2015 ICOHTEC/IEEE International History of High-Technologies and Their Socio-Cultural Contexts Conference* (Tel-Aviv: IEEE, 2015) <https://doi.org/10.1109/HISTELCON.2015.7307318>.

[250] S. G. McDaniel, *An Evaluation of a Honda 'Electro Gyro-Cator' Land Navigation System*, *Technical Report RG-83-16* (Redstone Arsenal, Alabama, 1983).

[251] Robert L. French, 'Historical Overview of Automobile Navigation Technology', in *36th IEEE Vehicular Technology Conference* (Dallas: IEEE, 1986) <https://doi.org/10.1109/VTC.1986.1623457>.

For the second time since the end of WW2, the US government had sponsored R&D that came very close to providing in-vehicle road navigation for motorists. In a technical sense, Transit-based navigation systems were entirely workable. Unlike with smart highway technology, the government paid the bill so that Transit satellites could be launched and the service could be improved over time. Seafaring industries and fields (and a number of wealthy boating enthusiasts) benefitted directly from the new navigation system. But because satellite system put the computational burden on the user's electronics, in-vehicle road navigation with Transit was stuck as a concept technology until the price of consumer electronics dropped substantially. In effect the bottleneck that was preventing in-vehicle road navigation from being deployed was moved outside of government control by the technical vision for satellite navigation.

Chapter 2 highlighted how government support was necessary for large technologies to get deployed in the post-WW2 period. With the continued evolution of consumer electronics, governments became a less decisive factor. The US government designed and built the Transit system. But by the 1970s that was no guarantee that consumer applications were incoming.

GPS and perfect timing

The inability of the Transit system to provide in-vehicle road navigation makes for an interesting contrast with the Global Positioning System (GPS). Even though GPS places the same burden on consumer electronics that Transit did before it, GPS has become wildly successful for in-vehicle road navigation. GPS succeeded in providing in-vehicle road navigation because it had perfect timing. This has something of a double meaning, since as I will explain in a moment, GPS' main innovation relative to Transit was to use atomic clocks rather than the Doppler shift to identify a user's location. But the extreme accuracy that GPS provides is not absolutely necessary for road navigation. The lower accuracy provided by Transit would have been fine as well. Rather, GPS succeeded because its deployment coincided with the development of other key technologies.

Most importantly, by the time GPS was made available to the public in the 1990s, consumer electronics had dropped in price to the point where the cost of buying one of the satnav receiver units was no longer prohibitive. By 2004 consumer electronics had come so far that Motorola was able to develop GPS receivers for cellphones, making it immediately possible for companies like Google to provide app-based road navigation—and indeed, Google Maps launched in February 2005.

The other bit of perfect timing that GPS was able to take advantage of was the creation of comprehensive digital road maps that covered the whole of the United States. The maps that are used today for in-vehicle road navigation are constructed in a series of layers.[252] At the bottom is a coordinate system with the basic geography included. From there, all sorts of other information can be added as another layer, linked through coordinates. The road network forms one such layer, points of interest form another, and so on. Buried amidst all the layers of data provided by commercial road mappers are the road maps provided by the US government. This is true even today, with companies like Google, TeleAtlas, and Here, building on a comprehensive road map called TIGER—the Topologically Integrated

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[252] More generally these maps are examples of what has come to be known as Geographic Information Systems.

Geographic Encoding and Referencing database—provided by the United States government since 1990, just in time for GPS road navigation.

It is worth mentioning TIGER's strange institutional history. TIGER is the de facto national road map in the United States, but unlike what you might expect, it is not provided by the Federal Highway Administration or the Geological Survey. Instead, TIGER is provided by the Census Bureau even though the agency has no real authority over the road system and has no institutional responsibilities around providing a road map of the United States.[253]

While agencies like U.S. Geological Survey, the Weather Bureau, the various branches of the military, and eventually the National Aeronautics and Space Administration all drew national maps for the issues that fell under their purview, road mapping was left unorganized at the national level. This institutional void complicated things for the private mapping sector, but it was able to stitch together the necessary information from state highway authorities without too much trouble. Rand McNally, for instance, invested in growing its map library after the second world war. Internal documents show that the company acquired virtually any map that state and federal agencies produced.[254] Its effort to repackage government map information as consumer goods became large enough that in

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[253] Now that TIGER exists, of course, the federal government expects the Census Bureau to provide and maintain its comprehensive road map of the United States, since other agencies depend on it. But it is not part of the original institutional mandate for the Census Bureau.

[254] Rand McNally Cartographic Research Department, *List of Maps Received from Sep. 1 1960 to Oct. 31 1960* (Skokie, IL: Rand McNally, 1960).

the early 1950s the company established a department to deal with acquiring and adapting third-party maps, separate from the department that produced original map products.[255]

Despite the commercial sector's success, the lack of a national road map created substantial problems for some government agencies, most notably the Postal Service and the Census Bureau. The Postal Service needed complete road information so that it could carry out its mission of providing mail and parcel delivery services. It ultimately dealt with this by developing zip codes to route mail and parcels to the appropriate regions, and once there, relying on its local offices to make sure that mail reached its destination. The Census Bureau had a more substantial problem since it was expected to enumerate every person in the United States for the decennial census. Without a road map, it would be easy for enumerators to miss a side street here or there, or even entire neighborhoods.

Enumerators began relying on maps with the 1930 census, when they had their areas of responsibility defined by a cut-out map, something which was only possible because the 1921 Federal Aid Highway Act required that states produce their own road maps. The dramatic improvement in rural road maps brought an equally dramatic improvement in the population and agriculture censuses.[256]

In the wake of the 1950 census a series of internal studies showed that reporting errors came more frequently from the enumerators than from respondents themselves. This prompted the realization that the Census Bureau may be able to produce more accurate

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[255] Duncan M. Fitchet, *Rand McNally Map Creative Departments* (Skokie, IL: Rand McNally, 1954).

[256] Clarence E. Batschelet and Alford Archer, *Comments on Geography and Cartography for Census Purposes Emphasizing Map Preparation for the 1960 Census of America* (Washington, D.C.: Bureau of the Census, 1956), p. 2.

data and save money at the same time if it only collected the census by mail, diminishing the role of enumerators and putting respondents front and center. But to do that the Census Bureau not only needed accurate maps, but a comprehensive list of addresses. None existed, whether at the Bureau of Public Roads or at the U.S. Geological Survey.[257]

Geographers at the Census Bureau developed two solutions. The first was the Address Coding Guide, a sophisticated method for identifying and maintaining digital records for every known address in the country. It needs to be said that this meant every address known to commercial mailing lists, as these provided the underlying data for the system. One crucial flaw necessitated the second solution: streets had no relationship to one another in the Address Coding Guide. While the system stored some geography in the form of zip codes, census blocks, and census tracts, enumerators needed to navigate the road system. Without a real map to help them, the Address Coding Guide could only do so much.

As a consequence, another team at the Census Bureau developed the Dual Independent Map Encoding (DIME), an early example of digital mapping. Like other digital road maps DIME represented the road system as a network, which allowed the topology to be edited in a more rigorous way. But DIME also went one step further by attaching the relevant range of addresses, drawn from the Address Coding Guide, to each stretch of road.[258] There was too much work to have it ready for the 1970 census, but the team did manage to extend it to 80 metropolitan areas and prepared coding manuals based on DIME for

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[257] Joseph J Knott, *Map Production and Related Geography Activities for the 1980's* (Washington, D.C.: Bureau of the Census, 1981), pp. 4–6.

[258] Knott, pp. 4–7.

enumerators there. The task of developing and maintaining DIME at the Census Bureau only grew over the next decade. To start with, DIME was expanded to cover the entire range of addresses that were included in the Address Coding Guide. It also needed to be updated and corrected. From 1975 to 1978 the Census Bureau made agreements to have local governments develop and correct DIME files. Local agencies would provide the staff, while the Census Bureau provided them with training, know-how, and money.[259]

The responsibility creep was not lost on the staff at the Census Bureau. In one document speculating on the future of DIME, looking toward the 1990 census, the Assistant Division Chief for Geoprocessing expressed some concern on that point, indicating that:

> "…the broader question becomes important: 'To what extent is the Bureau responsible for providing tools (GBF's, maps, etc.) to local agencies and private companies for use in planning, etc.?'. The Bureau supplies a lot of data, but should it also supply tools to help use the data?" [260]

As he explained, the Census Bureau had become one of the largest map preparation agencies in the world, if not the largest. This demanded large up-front investments into computer technology and human capital, but also imposed additional costs to maintain all that.[261] It also raised important questions about where the Census Bureau fit into the larger ecology of federal agencies.

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[259] Knott, pp. 7–9.

[260] Knott, p. 11.

[261] Knott, p. 13.

> "The question of where the Bureau fits in the Federal government's map making agencies is not yet settled. Census needs do not mesh well with other agencies' objectives. A census needs maps with wall-to-wall national coverage which is as current as possible. Because of the tabulation universe the Bureau is concerned about correct placement of invisible or intangible lines (corporate limits, many MCD-county-state boundaries, etc.) and somewhat less concerned with highly precise placement of ground features. Because of the census' unique needs, the Bureau will continue to have some type of mapping function even if USGS or some other agency is willing to take on a large part of the base preparation"[262]

Other agencies were better suited to providing a national road map. The Bureau of Public Roads—eventually renamed the Federal Highway Administration—was the most obvious, but the U.S. Geological Survey had its own ambitions in this space, bound up in its work toward a national atlas. But neither of these agencies had taken on the task of assembling a national road map, and neither of them needed addresses to do their work. This left the Census Bureau as the unlikely provider of the national road map, and other agencies came to rely on its work.

TIGER was an evolution of the DIME mapping system and was meant to solve the shortcomings associated with DIME's design. When it was launched in time for the enumeration of the 1990 US census, TIGER was equally primed to be incorporated into commercial mapping products. Early digital mapping companies like TeleAtlas and Navteq used TIGER as one of the fundamental layers in their digital maps. When Google Maps

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[262] Knott, p. 14.

began relying on its own data—it had originally used maps from TeleAtlas—it pulled in TIGER as a starting point as well.

This all meant that the 1990s were witness to the coming-together of a whole series of innovations that contributed to the technical guts of in-vehicle road navigation today. Consumer electronics finally made satnav receivers affordable, and work by the Census Bureau had just delivered a comprehensive road map of the United States. The final innovation, although not necessarily the most important one, ironically, has to do with GPS itself.

Designing GPS and releasing it to the public

While Transit revolutionized navigation over sea—and failed to do so over land—another satellite system was in development around the same time, the Global Positioning System. While Transit relied on the Doppler shift to identify someone's position in the world, GPS uses a much older technique called trilateration,[263] which uses the distance between its satellites and the observer to the same effect.

The basic idea of trilateration—to take the two-dimensional example—is this. If we know the position of two points (say, A and B) and their respective distances from a third point of interest (C) we can imagine that we have two circles. One circle is centered on A and has a radius that is exactly the distance between A and C. Our point of interest must lie somewhere along the outside of that circle. The second circle is similar, only it is centered

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[263] Trilateration is a bit of an ambiguous term since surveyors and mathematicians do not use the term synonymously. Engineers have come to call this true-range multilateration. I will stick with trilateration in the name of simplicity and readability, though. When I write trilateration, just know that I mean true-range multilateration, lest I confuse a surveyor or mathematician who happens across this research.

on B and its radius is exactly the distance between B and C. Our point of interest has to lie along the circumference of this second circle as well. By looking for where the two circles intersect we can pinpoint the location of C. As it turns out, when we know the location of two points, the solution provides two possible locations for C. But by incorporating additional circles (and extra points whose position we know) we can rule out the "wrong" answer.

By the lead-up to WW1 major powers like Austria, Germany, France, and Russia had already started to strategize how they could use trilateration to figure out the locations of enemy artillery. The principle was simple. Install high-quality microphones at dedicated stations and listen for the "boom" of an artillery shell firing. The difference in how long the sound took to travel to each respective microphone provided the information they needed to carry out the calculations.[264] The British were the first to implement the system during the war, using Australian scientist and British officer Lawrence Bragg to sort out the details. In 1915, while he was still working on implementing the British artillery sounding system, Bragg would find out that he had become a Nobel laureate for his work on X-ray crystallography with his father. As of this writing, he is still the youngest person to ever win a Nobel Prize.[265]

Trilateration became important to navigation itself by WW2, with the British investing in a system (the GEE system) that used the delay between radio signals to help its Royal Air

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[264] Claud Powell, 'Hyperbolic Origins', *Journal of Navigation*, 34.3 (1981), 424–36 <https://doi.org/10.1017/S0373463300048049>.

[265] William Van Der Kloot, 'Lawrence Bragg's Role in the Development of Sound-Ranging in World War I', *Notes and Records of the Royal Society*, 59.3 (2005), 273–84 <https://doi.org/10.1098/rsnr.2005.0095>.

Force navigate the skies. The Decca Record Company had designed yet another system—the Decca Navigator System—that used radio signals from a series of dedicated stations to help people navigate. Wartime Britain built this one as well, and even deployed it in its ships as part of the D-Day landings in June 1944.[266] As with the Transit satellite system in the US, however, these systems were never targeted for motor vehicles.[267] It took until the 1980s for researchers to give any serious consideration for how to adapt the Decca Navigator System for land navigation.[268]

It was not just Britain that developed navigation systems around this time using the principles of trilateration. In the United States, a system named Loran was built, using a very similar operating principle as the Decca Navigator system. In the wake of Transit's success in the early 1960s, American scientists began toying with the idea of developing a Loran-style system in orbit, in order to provide global coverage. The underlying trilateration technique would need to be updated to correct the additional complexities that would be presented by the system needing to operate in space. This marked the origins of the Global Positioning System.[269]

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[266] Claud Powell, 'Hyperbolic Origins'; W.J. O'Brien, 'Radio Navigational Aids', *Journal of the British Institution of Radio Engineers*, 7.6 (1947), 215–46 <https://doi.org/10.1049/jbire.1947.0024>.

[267] Walter Blanchard, 'The Genesis of the Decca Navigator System', *Journal of Navigation*, 68.2 (2015), 219–37 <https://doi.org/10.1017/S0373463314000666>; Claud Powell, 'Early History of the Decca Navigator System.', *Journal of the Institution of Electronic and Radio Engineers*, 55.6 (1985), 203–9 <https://doi.org/10.1049/jiere.1985.0069>.

[268] C. Powell, 'Performance of the Decca Navigator on Land', *IEE Proceedings F: Communications Radar and Signal Processing*, 129.4 (1982), 241–48 <https://doi.org/10.1049/ip-f-1.1982.0036>.

[269] Howard F. Marx, 'NAVSAT TO GPS: The Rocky Path to Success', in *46th AIAA Aerospace Sciences Meeting and Exhibit* (Reno, 2008) <https://doi.org/10.2514/6.2008-865>.

The immediate problem was that measuring the delay between radio signals, as the Decca Navigator System and Loran both did, became immensely complex in orbit. Too many factors promised to interfere with its accuracy, and the addressing the question of how many satellites would be required was equally daunting. But measuring the delay between radio signals was at its core just a nifty way of measuring distance. There were other ways of measuring distance.

The idea emerged that the satellites could be loaded with atomic clocks.[270] If the user down on the planet knew when the signal was sent, it would be possible to compare it with the time that the signal was received and using some relatively simple math the distance from the user to the satellite could be determined. With a constellation of satellites using this technique, it seemed possible for users to find their location anywhere in the world. There were still technical hurdles to be overcome, though. Much of this work was done by the Naval Research Laboratory.

Two research projects out of the Naval Research Laboratory were vital for the development of GPS. The first was the Minitrack, a set of ground stations that were designed to track the orbiting satellites, specifically the satellites the Navy intended to launch through Project Vanguard. Minitrack was successful not only in monitoring US satellites like Explorer 1 and Vanguard 1, the first two American satellites in space, but also in tracking the Soviet Union's Sputnik 1 and Sputnik 2. As the idea developed of using satellites with atomic clocks for global positioning, Minitrack found a second purpose. When the radio waves

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[270] Leo B. Slater, 'From Minitrack to NAVSTAR: The Early Development of the Global Positioning System, 1955-1975', *IEEE MTT-S International Microwave Symposium Digest*, 2011 <https://doi.org/10.1109/MWSYM.2011.5972582>.

given off by satellites like the GPS travel through the atmosphere, they are distorted in small ways. This risked undermining the whole reason behind using atomic clocks in the first place. With Minitrack, though, engineers realized that they could correct for this distortion using the satellite tracking data its ground stations provided.[271]

The second project that led to GPS was the development of the Timation satellites, which were crafted starting in 1965—the first Timation satellite would be launched in 1967—to evaluate the complexities of trilateration with on-board atomic clocks. By 1971 it had already become clear that the system worked.[272] Users on the ground could reliably determine their position using the clock information being relayed from the satellites. Over the next several years improvements were made to Timation satellites' inner workings, before the project was subsumed by the Air Force's Project 621B, which would eventually become the Navstar Global Positioning System. The quartz oscillators that were serving as atomic clocks were upgraded from rubidium to cesium,[273] and the structure of the signal that the satellites would send out was modified after long discussions between Navy and Air Force representatives.[274]

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[271] See Slater; R.L. Beard, J. Murray, and J.D. White, *GPS Clock Technology and the Navy PTTI Programs at the US Naval Research Laboratory* (Washington, D.C., 1986).

[272] T.B. McCaskill, J.A. Buisson, and D.W. Lynch, *Principles and Techniques of Satellite Navigation Using the Timation II Satellite* (Washington, DC, 1971).

[273] Rubidium clocks improved their capabilities beyond cesium clocks over the ensuing two decades, so that GPS satellites today have returned to using rubidium.

[274] Richard D Easton and Eric F Frazier, *GPS Declassified: From Smart Bombs to Smartphones* (Lincoln, NE: Potomac Books, 2013); Beard, Murray, and White.

While GPS satellites would be upgraded with each successive generation, the main technical architecture was settled by the late 1970s.[275] In the five years that followed, users at the Department of Defense requested that a low-cost version of the receiver devices be prioritized. The starting GPS satellites had been designed to send out two signal codes. One was termed the coarse-acquisition code (or C/A code), meant to allow users to quickly acquire the relevant information while giving up some accuracy. The other was the precise code (or P code), which as its name suggested was designed to provide a more accurate position, though the signal was much longer and thus much harder to acquire. The Department of Defense wanted an effective C/A signal receiver as soon as possible to start reaping benefits from GPS.

In 1983 the engineering team announced that it had run tests on the unit it had designed to receive the C/A code. The original expectation was for it to be only accurate to about 100m (Transit was accurate to about 200 meters). This is when things got tricky. Surprising everyone involved, the C/A receiver unit performed nearly as well as any positioning technology that existed at the time, showing itself to be accurate to somewhere between 20m and 30m!

Accuracy at that level would be enough to automatically detect what road someone is driving on, except in the densest road networks. And the benefits were just as high for oil exploration, surveying, shipping, military logistics and weapon delivery. Expectations around GPS soared. As it was put by two of GPS' lead engineers in the wake of these tests:

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[275] Paul E. Ceruzzi, *GPS* (Cambridge, MA: MIT Press, 2018), pp. 77–80.

> "What was started just ten years ago is now beginning to take the form of a real, operational system whose capabilities extend well beyond anything available today. We predict, as we did ten years ago, that GPS will revolutionize the art and science of navigation."[276]

In the same year these tests were announced, Korean Airlines flight 007 strayed from its route and entered Soviet airspace. The plane was shot down after being mistaken for an American reconnaissance mission. Realizing that had the plane been able to use GPS the incident could have been avoided, the Reagan White House announced that civilian aircraft would be given access to the GPS as soon as it went online.[277]

Ironically, though, the surprising accuracy of the C/A code posed real problems. The C/A code had been intended as a low-accuracy version of GPS that could be safely provided to the public, with the P code received for military use. If C/A receivers could be accurate to the tens of meters, suddenly this same code could become a threat to national security, as bad actors could use devices that had a large blast radius against the United States with almost perfect accuracy, and it would be accomplished using the country's own technology.[278] To deal with this possibility the GPS signals were re-designed. The P code was encrypted to prevent its use by anyone other than the US military and its allies. Meanwhile, the C/A code was artificially made less accurate through a policy known as

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[276] Bradford W. Parkinson and Stephen W. Gilbert, 'NAVSTAR : Global Positioning System--Ten Years Later', *Proceedings of the IEEE*, 71.10 (1983), 1177–86 (p. 1186).

[277] Larry M. Speakes, 'Statement by Deputy Press Secretary Speakes on the Soviet Attack on a Korean Civilian Airliner, 09/16/1983' (Washington, D.C.: White House, 1983).

[278] Parkinson and Gilbert; Ceruzzi.

"selective availability." Random noise was deliberately added to the publicly available C/A signal so as to reduce its accuracy to about 50m and avoid some of the most dangerous potential use cases.

This prompted a twenty-year debate in the United States government between those institutions that believed GPS held immense value to the economy and ought to be made available to everyone as soon as possible, like the Federal Aviation Administration and the Department of Commerce, and those institutions—primarily the Department of Defense—that believed GPS was a key military asset and ought to be secured from potential enemy uses. The issue cut to the core of what came to be known as "dual-use" technology. These were technologies developed for military purposes, but which had valuable spin-off potential for the economy. GPS was designed from the beginning for dual use, but the value to the economy came from the same accuracy that provoked national security concerns.

This internal dialogue was started under the Reagan administration, but little progress had been made up through the end of George H.W. Bush's tenure in the presidency. What forward motion had come was a result of the first Gulf War, which brought GPS to the public's attention, sometimes through the nightly news. The American military had used GPS guided missiles to dramatic effect. But in addition to that GPS helped guide troop movements in the field and had previously been used in Panama to help Navy minesweepers identify minefields with precision.[279] GPS devices were perceived as such a powerful tool that many service members, on their own initiative, asked their families back

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[279] Vincent Kiernan, 'Guidance from above in the Gulf War', *Science*, 251.4997 (1991), 1012–14 <https://doi.org/10.1126/science.251.4997.1012>.

home to visit army surplus stores to purchase civilian GPS receivers and send them to Iraq for them to use.[280]

When the Clinton administration took power in 1992 it quickly set about trying to mend the rift between civilian and military users of GPS. By this point in time, it seemed silly that GPS, which was already in demand and indeed in use by the former userbase of the Transit satellite system, was being deliberately held back in the name of national security. Scott Pace at RAND—and the former Deputy Director at the Office of Space Commerce within the Department of Commerce—framed the issue as a question of whether the United States would lead in the navigation industry going forward, or if some foreign power would take its place as the country dawdled over the dual-use debate:

> “Do you remember the TV ad by AT&T in which Tom Selleck's voice says that it will be possible to drive cross-country without a map? That's a sample of GPS and GIS blending to create a new consumer product. Unfortunately, I saw a similar TV ad two years ago featuring a young couple using a car-mounted GPS and CD-ROM map. It was in Japanese.”[281]

Pace was right of course, if a tad dramatic. Mazda introduced GPS navigation in the Eunos Cosmo in 1990, while in 1991 Toyota and Mitsubishi did the same for the Soarer and the Debonair, respectively. What’s more, Japan had funded intensive research into intelligent transportation systems throughout the late 1970s and early 1980s, after the United States

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[280] Ceruzzi, p. 113.

[281] Scott Pace, *GPS: Challenged by Success* (Santa Monica: RAND, 1993).

had given up on technology like DAIR and ERGS. American automakers were not far behind, mind you, and these vehicles were serving niche markets. But there was a very real possibility that Russia, Europe, or Japan—which were all planning to launch their own varieties of satellite navigation technology—could outmaneuver the United States and position themselves as the main provider of navigation services in the market.

The dialogue between the Department of Defense and Department of Transportation appeared promising at first, as the two bureaus were able to come to a quick agreement on the responsibilities they would each have in federal radionavigation planning,[282] and issued a report though a joint task force on the benefits and risks associated with various potential plans around GPS.[283] By 1995 though, after five years of policy progress, the Department of Defense had become unhappy with what it saw as misleading claims from agencies in support of ending selective availability.

News reached the White House about the change of heart in the Department of Defense in early 1995.[284] That same news found its way into trade magazines, prompting concerns from industry that selective availability would not end after all.[285] The administration scrambled to set up an interagency policy review to sort out the differences and get back on track, something the administration's GPS Industry Council had recommended to Vice-

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[282] *Memorandum of Agreement Between the Department of Defense and the Department of Transportation: Coordination of Federal Radionavigation Planning* (Washington, D.C., 1990).

[283] Joint DOD/DOT Task Force, *The Global Positioning System: Management and Operation of a Dual Use System* (Washington, D.C., 1993).

[284] *Point Paper on Wide Area Augmentation System (WAAS) Acquisition Program* (Washington, D.C., 1995).

[285] Lee Williams, *Letter from Lee Williams to Masha Scott* (Washington, D.C., 1995); GPS Industry Council, *Letter from Charles R. Trible to VP Al Gore* (Washington, D.C., 1995).

President Gore upon hearing the same rumor. As Lee Williams, one of Clinton's confidants in Washington, explained:

> "The alternative is to let the agencies—at the mid level—take pot shots at each other, let the press pick this up, let Congress jump in because Administration policy is lacking, and let industry be convinced that the Administration is not organized or doesn't care about the issue."[286]

On April 10th the Under Secretary of Defense Gil Klinger sent a letter to Arnold Donahue, the GPS Project Director for the National Academy of Public Administration,[287] which had just recently issued a draft report with the National Academy of Sciences on GPS and its potential for dual use. The Department of Defense took issue with many of the report's central claims, claims which, it should be said, had also been made in reports from RAND and the Office of Science and Technology Policy, and which would be repeated in the months that followed by the GPS Industry Council and the White House itself.[288] Most importantly, Klinger asserted that the Department of Defense had shared "extensive" classified information about US and foreign use of GPS, and that the report appears to have largely ignored that evidence in order to minimize the threat toward national security. It also called into question the core issue of whether selective availability was hampering

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[286] Williams, p. 1.

[287] Gil I. Klinger, *Letter from Gil I. Klinger to Arnold Donahue* (Washington, D.C., 1995).

[288] March Johansen, *Global Positioning System* (Washington, D.C., 1993); GPS Industry Council, *Can the U.S. Afford a Separate Military GPS System Acquisition When U.S. Policy on GPS/PPS Change?* (Washington, D.C., 1995); White House, *White Paper on GPS National Security Policy* (Washington, D.C., 1995).

growth in the GPS industry, as the National Academy of Public Administration's own report discusses how quickly that market is growing—all in the presence of selective availability.

One month later the Department of Defense sent another letter, this time to Dr. James Schlesinger, the author of the report from the National Academy of Public Administration and the National Academy of Sciences.[289] It expressed displeasure at how the comments issued by the Department of Defense on the earlier draft had not resulted in any substantive changes to the report and registered its opposition to the recommendations the report made.

Schlesinger made this disagreement public in a cutting speech he delivered in Palm Springs at a symposium on the impact of GPS, organized by the National Academy of Public Administration.[290] Explaining how the internal government discussions around GPS had come to an impasse, he said:

> "The DOD reaction has been to fight tooth and nail against the panels' recommendation. The DOD has stated that 'any change in the implementation of SA will be a virtually irrevocable step'. Why irrevocable? Is this an example of a perennial Pentagon fear that the final decisionmakers cannot be counted on to do the sensible thing in times of crisis? So why not limit their options? If the final authorities cannot be relied upon, selective availability should be on continuously. Scant consideration is given to the inconvenience and to the substantial and

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[289] Paul G. Kaminsky, *Letter from Paul Kaminsky to James Schlesinger* (Washington, D.C., 1995).

[290] James Schlesinger, *The Ultima Thule of Navigation: GPS* (Palm Springs, CA, 1995).

> growing costs to the civilian sector or to scientific measurement which result from selective availability being continuously on—ultimately to guard against the untrustworthiness of the highest authorities."[291]

And Schlesinger did not stop there. He mused at whether it was human nature to seek out problems and invent new challenges, since for most of human history the central risk of navigation was inaccuracy. Now that engineers in the military had created a tool that made the provided accurate navigation, the Department of Defense was desperate to solve a new problem. As Schlesinger put it: "if something is inaccurate, how do I make it accurate? But paradoxically if it is accurate, my God, how do I make it inaccurate?" He left the room with one final parting shot:

> "Let me close with this observation. It will be recalled that on his first voyage to America, Columbus kept two sets of charts—one to mislead his crew to prevent their worrying too much about their location, the other for himself—a dramatic if early example of selective availability. … Eventually it turned out that the charts for the crew, which were intended to deceive, were more accurate than the charts Columbus intended for his own use. Ladies and Gentlemen, there just might be a moral there. To be sure, Columbus' deception may have been more likely to succeed in fooling others than our own selective availability. Yet, in such deceptions, the real risk is that we may fool ourselves."[292]

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[291] Schlesinger, p. 6.

[292] Schlesinger, p. 8.

With the Department of Commerce, the Department of Transportation, the National Academy of Public Administration, the National Academy of Sciences, and the GPS industry council, the Clinton administration had secured enough allies to push ahead toward ending selective availability anyway. To that end, President Clinton issued a directive in March 1996, stating that selective available was to be phased out within 10 years, that period of time being a concession to the Department of Defense so that it could adequately prepare for the transition. After a few years of quick progress on the main issues, both technical and political, selective availability was turned off on May 2nd, 2000.

Figure 4 highlights just what a dramatic shift this brought about for the navigation industry. The average error in the estimates given by civilian GPS receivers went from 50m to about 4.6 meters (with 95% of the estimates falling within 6.3 meters).

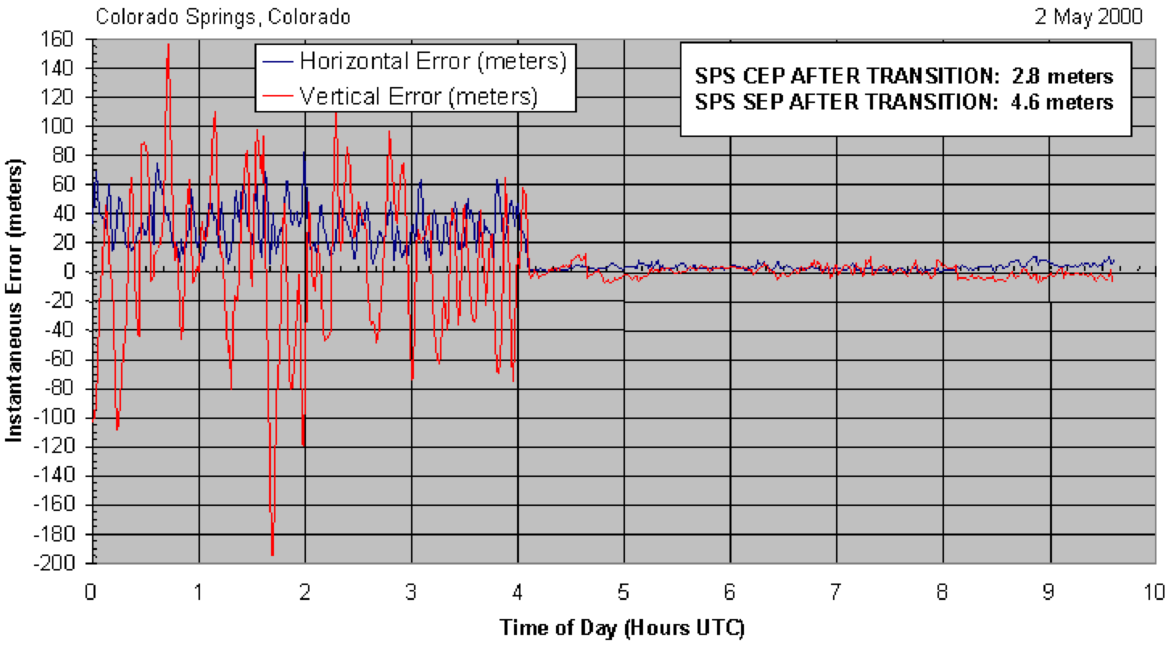

Figure 4: Errors in GPS positioning on May 2 2000, before and after the turning off of selective availability*. With the ending of the policy of selective availability GPS accuracy for civilians was improved from being on average accurate to just under 50m to under 5m. Figure is provided by the GPS Support Center at Air Force Space Command. Data were collected at an Air Force GPS monitoring station in Colorado Springs.*

Unintentionally innovative

GPS navigation is one of the federal government's more recent success stories around innovation. To be sure, GPS was built by the government, the digital road maps at the core of many applications were pioneered in government agencies, and the eventual decision to end selective availability prompted an explosion of R&D and innovative products built around GPS. But closer inspection of the history of how this developed and the numerous false starts along the way suggests that if the government was innovative, it was only unintentionally so.

Comprehensive digital road maps were not assembled for the sake of road navigation, but instead were happy accidents of institutional responsibilities gone awry. Even GPS itself was only released for public use reluctantly. When the government realized its engineers had come up with an astonishingly accurate system for positioning it did not work toward making that innovation available to consumers. Instead, it intentionally degraded the accuracy of the system and only reversed course after two decades of internal debate. This case of supposed government intervention and support for innovation is equally one where government actively suppressed innovation out of fear for how widely its creation would be used by hostile actors. Government was still powerful—its suppression of innovation was extremely successful—but it required considerable effort on its part to exert control in that space.

The period from the Second World War up through the early 1970s stands as a high-water mark for US government's impact on science and technology. So much so, that it has become a default reference point for scholarly and public debates about government intervention in the economy.[293] As was the case with weather forecasting, in-vehicle road navigation sits as an extreme example of government intervention in an already extreme moment of time. That said, one of the main advantages in studying in-vehicle road navigation around this period is that the sharp discontinuity before and after 1971, when Congress withdrew funding for smart highway research, provides some unique leverage in trying to understand government intervention. The two threads I followed in this chapter take advantage of the discontinuity in different ways.

With the first thread, where I tracked how the innovations from smart highways made their way to other industries and countries, the before-and-after comparison is especially useful. Chapter 2 showed that government's decision to withdraw funding from smart highway research effectively terminated R&D in government and industry alike, exhibiting exactly the sort of direction-setting that Polanyi first warned about. But the lesson of the before-and-after comparison here says something a little different.

Even if the government was responsible for launching smart highway research with its large investments into the interstate highway system and for terminating that same research, government intervention had not affected scientists' ability to search the landscape. Not only did the knowledge migrate to agriculture, yard care, and warehousing, but it did so while the government was still actively funneling money and human capital toward smart highways. If government intervention disrupted science's spontaneous

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[293] Desrosières; Foucault; Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*.

order, at the very least the effect was not categorical since the search process continued relatively unabated.

The US government also altered the landscape for research, creating new possibilities for in-vehicle road navigation through GPS and the work of the Census Bureau in creating a national map. This is another situation where government intervention has been hailed as a smashing success.[294] As I already noted, the main difference between these contributions and the technologies the government introduced to weather forecasting is that there was no intentionality behind it in this case. This is not entirely surprising, since it is common for the government to provide infrastructure on the grounds that there is a wide variety of potential users. But it is still an important point since it suggests that the debate around government intervention has long ignored a more general contribution in favor of focusing on the disruptive impact that governments can have.

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[294] Ceruzzi; Easton and Frazier.

Chapter 5:

Conclusion

Getting the most out of a complex system

Figuring out how to maximize the social benefits that are provided by science has been a point of discussion since the early 17th century, though it took on new importance thanks to the Second World War. The science of science came of age with the onset of the Cold War.[295] As I explained in Chapter 1, the result was that the debate around government intervention in science and technology was driven at least as much by ideology as it was by research.

Well-respected scholars like Michael Polanyi took to decrying proposals for government intervention in science as communism.[296] In his view, when left alone, science created "spontaneous order" that led to discovery and innovation. He agreed with his contemporary, Vannevar Bush, that the government should focus mainly on providing funding for research and leave the rest for science to sort out. [297] As time went on scientists

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[295] Derek J. De Solla Price, 'The Science of Science', *Bulletin of the Atomic Scientists*, 21.8 (1965), 2–8 <https://doi.org/10.1080/00963402.1965.11454842>; Maurice Goldsmith, 'Science of Science Foundation', *Nature*, 205 (1965), 10; Santo Fortunato and others, 'Science of Science', *Science*, 359.6379 (2018) <https://doi.org/10.1126/science.aao0185>; Dashun Wang and Albert László Barabási, *The Science of Science* (New York: Cambridge University Press, 2020).

[296] Michael Polanyi.

[297] Vannevar Bush, *Science: The Endless Frontier* (Washington, D.C.: Office of Scientific Research and Development, 1945).

of science continued to repeat this view, albeit while tamping down on the ideology,[298] bolstered by a slew of research that showed that markets can and do fail to provide as much funding as they should for R&D.[299]

Left unanswered was the question of whether government could intervene and direct research toward specific topics. The Manhattan Project and later the Apollo missions seemed to hold out the possibility that governments could make a positive impact in helping science along.

The original objection from Polanyi was that government intervention would mess up the productive spontaneous order within science.[300] Now, science is not always efficient in the first place, as the science of science has repeatedly shown.[301] Scientists follow trends,[302] they are risk averse,[303] choose topics based on the available research funding, and sometimes struggle to conduct an efficient search because of the information glut in science.[304] Despite these inefficiencies, though, the thousands upon thousands of scientists, all pursuing their own research projects, still continue to work like an efficient search

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[298] Nelson; Nelson and Langlois; Linda R. Cohen and Roger G. Noll, *The Technology Pork Barrel* (Washington: Brookings Institution, 1991) <https://doi.org/10.1017/S0003055400305524>.

[299] e.g. Arrow; Martin and Scott.

[300] Michael Polanyi.

[301] Kuhn, *Struct. Sci. Revolutions*; Feyerabend.

[302] Rzhetsky, Iossifov, and others.

[303] Foster, Rzhetsky, and Evans; Rzhetsky, Foster, and others.

[304] Swanson, 'Fish Oil, Raynaud's Syndrome, and Undiscovered Public Knowledge.'; Swanson, 'Medical Literature as a Potential Source of New Knowledge'; Chu and Evans.

team.[305] Science as a whole has a tendency to find the best ideas out of the myriad possibilities to help knowledge accumulate. But does that mean government interference would undermine that potential? Contemporary policymakers certainly hope not.

For my part, I have argued that governments mainly disrupt the search process in science in narrow ways. They can change the focus of specific laboratories and quicken or halt the development of specific technology. But scientists that fall outside of the government's intervention are still free to explore the landscape of possibilities. Furthermore, governments can have a profound impact on innovation by introducing new technologies and transforming the potential for research across various topics. In the two cases I considered here, this was by far the most significant way the government had affected the accumulation of knowledge.

Revisiting the logic of inquiry

The longstanding methodological quandary in the political economy of innovation is that even in cases where governments intervention does lead to positive outcomes, it is impossible to know whether that really owed to the actions taken by government or if hidden market mechanisms were responsible.[306] My methodological design shifts the focus slightly to avoid these problems. Rather than trying to weigh government intervention

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[305] Fleming; Fleming and Sorenson, 'Science as a Map in Technological Search'; Fleming and Sorenson, 'Technology as a Complex Adaptive System: Evidence from Patent Data'.

[306] Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*; Block; Nelson and Langlois; Philippe Aghion and others, 'Industrial Policy and Competition', *American Economic Journal: Macroeconomics*, 7.4 (2015), 1–32 <https://doi.org/10.1257/mac.20120103>; Dani Rodrik, *Industrial Policy for the Twenty-First Century*, 2004 <http://ssrn.com/abstract=617544>; Frank R Lichtenberg, 'The Impact of the Strategic Defense Initiative on US Civilian R&D Investment and Industrial Competitiveness', *Social Studies of Science*, 19.2 (1989), 265–82 <https://www.jstor.org/stable/285143>.

against market mechanisms, I take government intervention as a given and focus on identifying the effects that it has on innovation in science and technology.

Comparing government intervention in and around weather forecasting and in-vehicle road navigation provides a fair bit of leverage in this regard. While the socio-technical systems in each case were elaborated through R&D during the 1950s and 1960s, there was a decisive break in 1971 when Congress withdrew funding for in-vehicle road navigation technology. This creates two main lever points for sussing out how governments shift the processes behind innovation. The first is with the before-and-after differences around in-vehicle road navigation itself, which went from being strongly influenced by the government to a situation where its innovations survived despite the government's neglect. The second is the explicit comparison between the way government entered into R&D around weather forecasting and in-vehicle road navigation. Here, too, the most useful contrast comes after the cases diverge, but the between-case analysis allows for more contemporaneous observations of the differences in government impact.

Looking past "picking and choosing"

Adjusting the methodological approach also meant that I needed to reframe the issue theoretically as well. Instead of taking for granted that government intervention distorted the spontaneous order in science, I have tried to specify exactly how government affects the achievement of that spontaneous order. My approach focuses on two contexts around R&D.

The first context is centered on the economic pre-requisites for research. Researchers choose their topics based on what they think will be a valuable use of their time and resources. With pure science this judgement can be made on an intellectual basis—will it advance knowledge in the field? In the case of more applied research the decision is grounded more firmly in market conditions—are there buyers and users for the idea?[307] If the general impression is that the idea has no intellectual merit on its own and that there is no viable market for it either, researchers will choose something else to work on. Dosi has previously referred to this as the first-order selection of research trajectories.[308] The first opportunity for government to influence the direction of research comes here, to the extent that government can provide a market (or the impression of one) for research on specific topics.

This was illustrated in dramatic fashion with the socio-technical systems at the heart of the present dissertation. R&D on numerical weather prediction was able to consistently move forward thanks to the knowledge that government had shown interest in the topic and had even deployed considerable resources to make it happen. More tellingly, government fostered that progress even though numerical weather prediction was impractical until the mid-1950s. Even as that happened numerical weather prediction was limited by the available computational power.

In-vehicle road navigation had the same experience up through the 1960s. Companies like General Motors and RCA began work on smart highway technology almost as soon as the federal government had begun planning the interstate highway system. Regular

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[307] Please note that this is an oversimplification. These evaluations are colored by scientific culture. Scientists take cues from one another in judging whether something is worth investigating or not. See Kuhn, *Struct. Sci. Revolutions*; Lakatos; Rzhetsky, Iossifov, and others.

[308] Dosi; cf. MacKenzie, 'Economic and Sociological Explanations of Technological Change'; Basalla.

collaboration with state highway authorities and the Bureau of Public Roads kept up the impression that there was a market for this technology, and the Bureau of Public Roads even launched its own intensive research project on the topic in the late 1960s. As Chapter 2 explained, this all ended in 1971 when Congress decided to withdraw funding for smart highway research. This provides the single best piece of evidence that government has a decisive impact on the direction that innovation takes, as R&D on smart highways stopped almost immediately in the United States.

The second context that matters in my theoretical approach has to do with the search for knowledge in science and technology. I explained in Chapter 1 that Polanyi's idea that science produces a "spontaneous order" when left alone is based on the same reasoning that underpins market mechanisms (and even biological evolution). I gave the metaphor of an expedition that sets out to find the tallest mountain in the world. With just one expedition exploring the planet's mountain ranges, it may take them a very long time to find the tallest peak, if they find the right answer at all. However, if thousands of expedition teams set out to find the tallest peak, someone is virtually guaranteed to come back to tell the world about Mount Everest. Science is meant to work through the same process, where thousands of researchers set out to find the right answer. While they may all look in different places, some scientist seems bound to the right answer thanks to the spontaneous order that arises from all this activity.[309]

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[309] Fleming; Fleming and Sorenson, 'Science as a Map in Technological Search'; Fleming and Sorenson, 'Technology as a Complex Adaptive System: Evidence from Patent Data'; cf. Avin.

Seen in light of this expeditionary metaphor, the concern is that government intervention more or less tells scientists where to look. If the government chooses wrong, it may take some time to find the tallest peak, even with thousands of expeditions. Why mess with a good thing?

I contrasted this view with the idea that governments change the landscape itself by providing new technologies to scientists. When they do so, it is as if they make certain mountains taller, and some valleys deeper. Scientists may choose topics differently because the government intervened, but in these circumstances they do so because the right answer changed, not because the spontaneous order in science was disrupted.

Chapters 3 and 4 leveraged the different trajectories of weather forecasting and in-vehicle road navigation to see just how well the idea that governments disrupt the spontaneous order in science holds up empirically. If government intervention leads scientists to do research on specific topics, abandoning the benefits of spontaneous order, it would surely leave a mark on weather forecasting, which had experienced persistent and pervasive government attempts to champion numerical weather prediction. Similarly, the sudden absence of government intervention around in-vehicle road navigation would surely affect the course of innovation in that area.

The evidence was more ambivalent. When it came the weather forecasting, the government's attempts to facilitate research around numerical weather prediction were not always successful. There was an immediate effect on researchers when the government provided the funds and workers for a weather balloon network, and when it supplied cutting-edge computer technology to the Weather Bureau. In so doing the government removed two of the main roadblocks for numerical weather prediction: the lack of data in the upper atmosphere, and the inability to do the necessary math fast enough. Numerical weather prediction went from an impracticality to one of the largest research areas in meteorology. Just as impressive for the government, its investments in data collection and computing power were major factors in how and when the socio-technical system for numerical weather prediction would evolve. Through its interventions the government had clearly changed the minds of researchers about the potential of numerical weather prediction. But it is not immediately clear that this happened because the government had disrupted the search process within science. On the contrary, it seems more accurate to say that the government had changed the size of the mountain in order to attract more research to its preferred topic.

Not everything went this smoothly, of course. Radar and satellites were big ticket items that the government hoped would have a similar effect in moving along the research in numerical weather prediction. They were both powerful new technologies that could document parts of the atmosphere that weather balloons did not reach. The trouble, as Chapter 3 explained, was that both technologies produced images as their fundamental result rather than numbers. This meant all the government investment that went into radar and satellites did very little to tempt researchers into doing more research on numerical weather prediction until new instruments were developed to allow the two technologies to produce numerical output. Fortunately, the spontaneous order in science won out and researchers interested in the older synoptic techniques for weather forecasting found immense use in the images in the meantime. Here again it does not seem quite right to say that government intervention disrupted the search mechanism in science. Government investments around radar and satellites very clearly failed to attract researchers to preferred topics like numerical weather prediction, and only succeeded in drawing more attention to the aging techniques that meteorology had long been hoping to move beyond.

If the impact of government intervention was not as disruptive as expected with weather forecasting, neither was its withdrawal as noticeable as expected with in-vehicle road navigation. As I mentioned above, Congress' decision to stop funding smart highway research in 1971 halted industrial R&D into the topic almost immediately. This is the clearest sign that government intervention had altered the search for new ideas. But even still, researchers had taken the same magnetic wire technology and started applying it to new problems in warehousing and agriculture even before the government had withdrawn funding to smart highways. The peak interest in these applications started before 1971 and continue well past it, suggesting that whatever distortion the government had created in the search mechanism in science was only affecting the motor vehicle industry. It had not undermined the ability for researchers to explore the wide variety of potential uses for the technology, or their collective ability to redistribute their efforts accordingly.

Maybe more interesting is that these developments built on top of the innovations that stemmed from the government's interventions around smart highways. Like its effect in weather forecasting, government intervention around in-vehicle road navigation changed the very landscape that science was meant to explore. This allowed follow-up research into the same technology in Japan and Germany, as well as the spillovers to warehousing and agriculture.

The landscape-transforming potential of government intervention is also demonstrated by the developmental history of satellite navigation. Some of the government's contributions toward the development of modern in-vehicle road navigation came entirely by accident, like when the Census Bureau developed a comprehensive digital road map of the United States to better carry out its more fundamental work in enumeration. The development of navigation satellites like Transit and the Global Positioning System, meanwhile, were obviously intentional, though they were meant primarily for military users. In any case by the early 1990s the government had so altered the landscape of possibilities for scientific research that that university researchers and industrial laboratories alike were clamoring for better access to GPS signals so they could be used in a wide range of applications. What's more, the same developments had inconvenienced the government's own agencies. The Census Bureau had never intended to become an industrial mapping outfit. Nor had the military planned on turning over its logistical advantage in satellite navigation to civilians. Neither agency won the day—the spontaneous order in science did.

	Weather forecasting	In-vehicle road navigation
Government and first-order selection		
Government sponsorship	Consistent	Withdrawn in 1971
Research halts?	No	Yes, after 1971
Government impact when research is ongoing		
Government attempted to direct researchers directed toward specific topics?	Yes	Yes
"Spontaneous order" still apparent?	Yes	Yes
Landscape of research possibilities changed by government intervention?	Yes, especially with weather balloons and computers.	Yes, magnetic wires influence innovation in nearby fields. GPS and the TIGER shapefiles allow for modern in-vehicle road navigation technology.
Government contributions came because of planned intervention?	Yes	No. Original intention for magnetic wires was for smart highways. With GPS navigation, government agencies are caught off-guard by the interest in their innovations.

Table 4: Summary of case evidence. *Note that while the US government had a clear and decisive impact on whether research moved forward in specific industries, its impact on the underlying search process in science was more limited. Research around numerical weather prediction was not dictated by the federal government, even as it was prioritized. Conversely, doing away with government support for in-vehicle road navigation did not undermine knowledge accumulation. It just removed the incentives toward smart highway research. Meanwhile, government intervention had a discernible effect on the landscape of possibilities for science, both when the government intended to do so and when it did not.*

The landscaping state?

Table 4 summarizes the main details of the cases, so far as they pertain to the argument. Looking only at the issue of first-order selection—that is, of the ability for government to provide researchers with the impression that someone will buy their innovations if they develop them—the old bugaboo around government intervention carries some weight. The withdrawal of funding from in-vehicle road navigation marks the moment where its outcomes start to diverge from those around weather forecasting. Within the case of in-vehicle road navigation itself, 1971 stands as a clear cut-off point for industrial R&D around the topic. The apparent interest shown by the government in sponsoring in-vehicle road navigation technology was the decisive factor in keeping the research trajectory afloat. Research was re-allocated almost immediately when that interest evaporated.

However, on closer inspection of the actual mechanisms involved, government intervention seems neither as risky as its critics would have it, nor as powerful as its proponents suggest. Why should it not be as risky? If the work of thousands of independent scientists leads to a "spontaneous order" that sifts the best ideas from the rest,[310] then my two cases provide very little evidence that government intervention disrupts knowledge accumulation.[311] Researchers quickly realized weather satellites still held value for synoptic weather forecasting, and that the magnetic wire technology in smart highways

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[310] Michael Polanyi; Hayek.

[311] Somewhat similar results about government funding specifically can be found in Paul A. David and Bronwyn H. Hall, 'Heart of Darkness: Modeling Public-Private Funding Interactions inside the R&D Black Box', *Research Policy*, 29.9 (2000), 1165–83 <https://doi.org/10.1016/s0048-7333(00)00085-8>.

held value for warehousing and agriculture. This mitigated a lot of the downside that came from the government choosing to sponsor the wrong technology.

Furthermore, the government also took on a landscaping role in both cases. As I described it earlier, it was as if the government made certain mountains taller. Its interventions changed the fundamental potential around specific research topics, drawing in researchers not just by distorting the search process, but by altering the very landscape that was being searched. I do not have the data to put a number to how much value was lost thanks to government intervention. But with every innovation that draws on the new technology provided through government intervention, that number becomes smaller.[312]

Why should government intervention not be as powerful as its proponents suggest, then? The past two decades of research on industrial policy and the developmental state give the impression that government intervention has been effective in growing economies around the world because the strategic choice of a direction for the economy can yield large returns.[313] By contrast, what my research shows is that most of the benefits from government intervention into weather forecasting and in-vehicle road navigation have not come from the government picking a direction—which did not always work, anyway—but from its impact in changing the research landscape for scientists.

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[312] cf. Fleming and others.

[313] Robert H. Wade, 'The American Paradox: Ideology of Free Markets and the Hidden Practice of Directional Thrust', *Cambridge Journal of Economics*, 41.3 (2017), 859–80 <https://doi.org/10.1093/cje/bew064>; Block; Matthew R. Keller and Marian Negoita, 'Correcting Network Failures: The Evolution of Us Innovation Policy in the Wind and Advanced Battery Industries', *Competition and Change*, 17.4 (2013), 319–38 <https://doi.org/10.1179/1024529413Z.00000000041>; Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*; Peter Evans; Chris Freeman, 'The "National System of Innovation" in Historical Perspective', *Cambridge Journal of Economics*, 19 (1995), 5–24 <https://doi.org/10.1093/oxfordjournals.cje.a035309>.

This may seem like splitting hairs, but the difference is substantial when it comes to the types of policies that are implied. On the one hand, if direction-setting or "picking and choosing" is what makes the difference for government intervention, then mission-oriented innovation makes a lot of sense. Governments can use their power to channel more research toward things like renewable energy and artificial intelligence. On the other hand, if direction-setting has a questionable success rate and the real value comes from introducing or helping to develop new technology, then mission-oriented innovation may simply be an ineffective policy intervention. Instead, it would make more sense to increase spending on government laboratories and to deploy more scientific infrastructure.

It is not a bold stance to say that both sides of a longstanding debate ought to temper their expectations and move toward the middle, though that is certainly what my research suggests. More interesting is that the idea of the landscaping state provides a unique avenue for incorporating the government into the existing understanding of science as a complex system where scientists search for new combinations of ideas on a research landscape.[314]

One of the challenges in the discourse around government intervention is that it pits the concrete reality of governments against the idealized model of science or markets. Research has tried to close this gap, but the incommensurability persists. Allowing the possibility that governments affect the research landscape makes it feasible to think about

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[314] Fleming; Martin L. Weitzman, 'Recombinant Growth', *The Quarterly Journal of Economics*, 113.2 (1998), 331–60 <https://doi.org/10.1162/003355398555595>; Martin L. Weitzman, 'Hybridizing Growth Theory', *The American Economic Review*, 86.2 (1996), 207–12 <https://www.jstor.org/stable/2118124>; Fleming and Sorenson, 'Science as a Map in Technological Search'; Fleming and Sorenson, 'Technology as a Complex Adaptive System: Evidence from Patent Data'; Basalla; Arthur, *The Nature of Technology: What It Is and How It Evolves*.

how government intervention feeds into market mechanisms or into science's "spontaneous order" and vice versa.

The government's role in shaping the research landscape opens the door for a number of interesting lines of inquiry. For instance, are there specific types of technology that the government should prioritize if it wants to impact science in this way? Things like computers and satellites are especially costly technology, as I have pointed out before. One of the few areas that economists agree that government intervention can be positive is with exactly this type of high-risk good. Does the same thing hold for the ability of governments to affect the research landscape?

Another fascinating follow-on question is whether and to what extent it matters that the research landscape—that is, the scientific or engineering value in a given combination of ideas—changes from field to field or even from application to application. The history of satellite road navigation seems to indicate that governments can be just as impactful by unintentionally altering the research landscape, since developments in far-flung fields can still bring surprising new possibilities. In this way, it may be that while government intervention can often be seen as changing the research landscape, changing the research landscape need not stem from government intervention, but merely government action.

The main difficulty in understanding the landscaping function of government is, and almost certainly will continue to be, judging whether government intervention has shifted the research landscape in the first place. In this way it resembles market mechanisms and science's spontaneous order, which also involve a degree of blind faith that invisible processes are finding optimal solutions. Rather than bringing more concrete detail to markets, the landscaping metaphor idealizes government intervention to make it easier to reason with alongside idealized market mechanisms

This is bound to be unsatisfying for empirically minded researchers. Fortunately, the specific details of how government intervention affected innovation are visible in my two cases and hearken back to factors that are more familiar and easier to document in the real world.

At the core of the story is the process of diffusion. The downsides of government intervention were mitigated by the way knowledge spreads over space and across domains, just as new possibilities for innovation emerged thanks to the same process. As I mentioned just a moment ago, there is no single research landscape around science and technology. Instead, the possibilities change depending on the application and the domain. While this is hard to prove empirically, this seems to be why diffusion adds so much complexity to the study of government intervention. All is not lost if the government chooses wrong with technologies like smart highways and their magnetic wires. Those same ideas can migrate to other domains, like warehousing and agriculture, where they can fill a much bigger need.

Moreover, the clearest success stories for government intervention in this dissertation saw the government actively trying to help technology diffuse, as it did with computers and weather forecasting. I argued in Chapter 1 that this resembles the technology brokerage that Hargadon and Sutton analyzed for firms more generally.[315] The point is that diffusion

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[315] Hargadon and Sutton; cf. Samford.

is not automatic. While ideas can absolutely spread without too much care and attention, much of the time someone needs to make an intentional decision to transfer innovations from area to another. This has been noted before about the developmental state, and the role it can play in importing cutting-edge technology from advanced economies.[316] Just within the past few years as well, Steven Samford documented how states can impact the diffusion of technology across firms in an industry, taking on a distinct role with regard to the developmental state, one that demanded a different set of network ties as compared to those required by Evans' more traditional idea of embedded autonomy.[317] My findings contribute to this budding line of research by extending the same ideas to diffusion across fields, and considering the way they affect the overall impact of government intervention.

The other way diffusion comes to matter is in a more negative sense. Diffusion is not automatic and like the narrative showed around radar and weather satellites, taking on the role of technology broker is no guarantee that the government's efforts will be successful in generating more scientific research. The main problem is that diffusion suffers from a certain friction when an idea or technology clashes with day-the-day workings and organization of scientists.[318] Just as all the various collaborators around a given project, professionals scientists or lay people, need to be made (and kept) interested in the project's framing of the problem, lest the collaboration break down, innovations can only

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[316] e.g. Negoita and Block.

[317] Samford.

[318] e.g. Ryan and Gross; Banerjee and others.

make an impact upon their diffusion if they can be incorporated into this same collaborative project.[319]

This is ultimately what limited the upside of government intervention around weather forecasting. Despite weather forecasting being an immense success story for government intervention in 20th century scientific research, in cases like radar and weather satellites—some of the biggest ticket items that government invested in—government intervention had a more ambivalent effect. The issue of how well innovations fit with the existing assemblage around scientific research is one of the local factors that shape the effect governments have on the research landscape.

Over and above the provision of technology, these processes around diffusion are the primary mechanisms through which government's landscaping impact was created. The landscaping metaphor itself may serve more of a heuristic role in future work, but the underlying mechanisms are concrete and observable, though also a bit unpredictable in their effect.

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[319] Didier; Law and Callon; Latour, *The Pasteurization of France*; Desrosières; Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*; Pinch and Bijker.

Powerful state or peculiar technology?

The research here was handicapped from the beginning. I have focused on what is probably the most promising and/or scary period of government intervention in science and technology for the United States, the period from the 1940s to the early 1970s. If there was a moment in time where government intervention was going to be decisive in turning scientists from one topic to another, this was it.

I mentioned in Chapter 1 how public discourse and academic debates alike point back to this era when they bring up government intervention in science and technology. This was the time of the Manhattan Project and the Apollo missions. It was the origin of satellites and marked the rapid growth of commercial aviation. Policymakers and scientists have continued to valorize this moment in time as they call for "new" Manhattan Projects or Moonshot 2.0's to address issues like climate change and cancer.[320] Despite all this hullabaloo, my findings suggest that the reality was far tamer. Government certainly had an impact on innovation, but it was mainly in circumscribing the search space and changing the shape of the landscape that was being searched.

In my discussion above I raised the question in a few different ways of whether the effect that government intervention is peculiar to the type of technology was involved. For weather forecasting and in-vehicle road navigation, there is one conspicuous detail to the history that suggests that policymakers would do well to stop drawing comparisons to this moment in time. Namely, as I have mentioned several times in this dissertation, early

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[320] For even more examples, see Mowery, Nelson, and Martin.

digital computers represented a fairly unique form of technology.[321] They were large and expensive, even as they promised to make difficult and time-consuming calculations into something routine. As a result, there was a lot of value to be had for society if computers could be integrated into more systems, but businesses were badly positioned to do that because of the risk involved in developing and deploying the necessary technology. Governments, though, could take those risks.

One of the recurring themes in the history of weather forecasting and in-vehicle road navigation is that computers dictated the evolution of the two socio-technical systems. Weather forecasting models expanded just as quickly as the computing power would allow. Smart highways, meanwhile, supplied the technical vision when computers were bulky and expensive, but they faded into obsolescence as electronics became smaller and more affordable. This also shifted the technical vision for in-vehicle road navigation, moving computers from the roadside to the in-vehicle device. One quirky consequence was that in-vehicle road navigation, despite being worked out over the course of the 1950s and 1960s, was delayed by thirty years while industry waited for the technology to grow small enough and affordable enough to make it a worthwhile purchase for the average driver.

Government intervention around weather forecasting and smart highways was impactful not just because the US government was especially ambitious from the 1940s to the 1970s—which it was, just to be clear—but because computer technology was impactful, and because the government could provide it. The coincidental timing of the neoliberal

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[321] For another take on what makes the post-WW2 period an awkward comparison for modern science policy, see Mowery, Nelson, and Martin.

takeover of government policy that started in the late 1970s obscures how technology shaped the possibilities of government intervention.[322] Small government and laissez-faire policy did empower markets in the United States, but so too did the shrinking size and price tags of computers and consumer electronics.[323]

Conclusion

The longstanding debate around government intervention in science and technology is heavy on ideology and light on substance. Without a doubt this is the historical legacy of how the science of science emerged in the early years of the Cold War, with commentators like Michael Polanyi raising the specter of communism.[324] With any luck this dissertation has advanced not just the empirical evidence around government intervention but also the theoretical base.

Science is a complex system made up of countless researchers, not only at universities, but also at laboratories in industry and government alike. There is a lot of merit in the idea that science a whole works like a decentralized "search" for innovations, and that it should be meddled with as little as possible. But the ever-present—and growing—risks around climate change have prompted scholars and policymakers alike to wonder if the government could speed up the transition to more environmentally friendly energy and

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[322] Rebecca Lave, Philip Mirowski, and Samuel Randalls, 'Introduction: STS and Neoliberal Science', *Social Studies of Science*, 40.5 (2010), 659–75 <https://doi.org/10.1177/0306312710378549>; Foucault.

[323] See the following work, for an especially compelling example of the impact of computer technology on the financial market, Donald MacKenzie, 'Material Signals: A Historical Sociology of High-Frequency Trading', *American Journal of Sociology*, 123.6 (2018), 1635–83 <https://doi.org/10.1086/697318>.

[324] Michael Polanyi.

technology. I believe they are right to do so. But I also think that we know relatively little about how government intervention affects the accumulation of knowledge, apart from what the literature on markets implies.

That being said, there are a few notable limitations to this study. One, as I just mentioned, is that the post-WW2 period is unique because of the state of digital computers at the time and the rise of neoliberalism thereafter. Relatedly, large-scale R&D was commonplace in the federal government from the early 20th century all the way through the 1960s, in a way that it was not for afterward.[325] This makes it hard to say with any certainty how far the lessons here generalize to other cases. I suspect that the overall argument about government intervention and its impact on the search mechanism in science and the research landscape applies just as well today as it did back then. But it needs to be kept in mind that the roles governments play in the economy have changed over time, and thus while the concepts and principles in my findings probably generalize, the details almost certainly vary in different times and places.

In addition to the period effects themselves, it ought to be said that historical and comparative research are hard pressed to describe the actual processes within a complex system. Now, this is not unique to history and comparison, but it does suggest that more theoretical and modeling work will be needed to put the conclusions I have reached based on the archival record on more firm footing. That said, I have tried to argue that historical methods still offer a number of advantages—advantages which I think far outweigh the shortcomings. Provided that the available archival materials allow it, history affords the

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[325] Leydesdorff and Etzkowitz.

possibility of looking at long-term processes by highlighting changes over time and evaluating key junctures in the history to see how well theoretical expectations hold up under scrutiny. Additionally, history can draw on a rich tradition of qualitative methodological techniques like ethnomethodology and actor-networks, which are inherently well-suited to studying complexity. While the documentation may be lacking for the historical study of complex systems, depending of course on what was recorded and what survived, the conceptual apparatus is more than capable.

The more important limitation for my research is that knowledge accumulates in different ways with different types of technology. One of the classic distinctions is between electronics and chemicals. Electronics by their very nature are a combination of components. This makes it possible for lots of innovation to stem from the introduction of a single new component, whether something on a small scale like a transistor, or something on a large scale like radar. Innovation around chemicals is much more discrete. While new research builds still builds on old research, the characteristics of new chemicals can be difficult to predict, making it much harder for any innovation to play the role that transistors or radar plays in electronics. But this also means that governments are unlikely to contribute in the same way in fields like chemistry. First-order selection is especially likely to be affected.

There is a similar problem that exists around scale and cost, where governments play a fairly distinctive role with the largest and most expensive technologies. Government is the largest provider of large technical systems and infrastructure because there are inherent risks with developing something so large and costly, and because managing expansive systems requires an expansive organization. In sharp relief, governments tend not to get involved in providing consumer products, since businesses are already perfectly capable of supplying them. It would be unreasonable to expect the government to have the same impact in fostering innovation around the smallest and most affordable technologies as compared to the largest and expensive.

It is exciting to learn that government intervention is boring. Its consequences are not nearly as bad in the worst-case scenario as critics would have it. But nor are its benefits as dramatic as its proponents suggest. Leaving aside its major role in funding science, government impact is limited to tilting the scientific field toward its preferred topics and joining in as a supplemental producer and buyer of innovation.[326]

And yet, it is still more interesting to see the government's surprising ability to change the research landscape itself, affecting the possibilities around specific ideas and technologies rather than just incentivizing research on them. I think this provides a useful corrective to a literature that has a tendency to study governments from the perspective of markets, rather than on its own terms. As enticing as markets can be as analytical devices, they oversimply how many non-market actors work.

The same thing is true for Polanyi's old idea about spontaneous order in science. It is a compelling framework for understanding government intervention in science. But as scholars like Rosenberg noted more than fifty years ago,[327] the fact that knowledge begets

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[326] cf. Naomi Oreskes, *Science on a Mission: How Military Funding Shaped What We Do and Don't Know about the Ocean* (Chicago: University of Chicago Press, 2021).

[327] Rosenberg; Nelson.

more knowledge creates a fundamental problem in tallying up whether government intervention is wasteful. However, what I have been able to do in this dissertation is to skirt this issue and answer something related, namely whether government intervention significantly disrupts the search processes in science and the spontaneous order they produce. The answer appears to be no, or at least not in any significant way.

For governments to be able to make significant contributions when they provide infrastructure-style technology that scientists can build upon suggests a better avenue for understanding government-market-science relationships from an academic perspective. But it also suggests that infrastructure-style policies may be an effective tool for mission-oriented innovation and “moonshots.”

All that being said, the limitations in my research design leave a lot of room for other scholars to refine and build upon the ideas I have presented in these pages. But in a dissertation on the accumulation of knowledge, that really is part of the point. Cheers to the next researcher.

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