Available online at www.sciencedirect.com
ScienceDirect
Geoforum 39 (2008) 3–16
GEOFORUM
www.elsevier.com/locate/geoforum

Geoforum Lecture 2007

Geography's underworld: The military–industrial complex, mathematical modelling and the quantitative revolution

Trevor J. Barnes

Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC, Canada V6T 1Z2

Received 12 August 2007

Abstract

The Second World War marked an epochal change in the relation of geographers to war and the military. The military had long utilised the skills of geographers, but from World War II the relation changed at least in the United States, and the military began less drawing upon existing geographical knowledge than directing a new kind that was increasingly formal, instrumental, and model driven. With the growing importance of the computer, this trend continued even more strongly during the early Cold War period, and was further propelled by the interests of a new, collective assemblage, the military–industrial complex. A cyborg entity, the military–industrial complex enfolded diverse performances, ideas, inanimate objects, people and even academic disciplines into a larger composite, one product of which was a new regime for the production of knowledge. The purposes of the paper are to examine the process by which geography within the United Stated joined this cyborg entity, and the character of the disciplinary knowledge regime that eventuated. The argument is pursued by examining three individuals key to the new disciplinary regime: Waldo Tobler a pioneer of analytical cartography and later GIS whose first job was at RAND on a project to develop an early warning system for nuclear attack; William Garrison who spearheaded the use of economic modelling in studies of transportation that he carried out with his students at the University of Washington Seattle; and Arthur Strahler, a geologist at Columbia University, who through his links to the US Office of Naval Research, funded and directed a set of students who later entered physical geography utterly transforming it to meet the dictates of the new regime.

Keywords: Cold War; History of American geography; Military–industrial–academic complex; Mathematical modelling

> American geographers have memorialised a "quantitative revolution" in research and application almost exclusively confined to academic geographers flowering in the 1960s. That flowering occurred when it did because the geo-spatial convergence of the Military–Industrial–Academic Complex had already spent over a decade following the quantitative road.
> John Cloud (2002, p. 268).

1. Introduction

Underworld, DeLillo's (1997) epic novel of life in Cold War America under the shadow of the bomb, begins the afternoon of October 3rd, 1951 at the Polo Grounds, home to the New York Giants. It is the deciding game of the National League pennant race. The Giants are playing the Brooklyn Dodgers. "Ol' blue eyes" Frank Sinatra, comedian Jackie Gleason, restaurateur Toots Shor, and the man with all the secrets, FBI Director, J. Edgar Hoover, banter between innings. At the bottom of the ninth, the Giants are 4-2 down, two runners on, one out. Like confetti, ripped pages suddenly begin to rain down from the upper decks, torn from magazines, newspapers, and programmes. Half of Peter Bruegel's *The Triumph of Death*, pulled from *Time Magazine*, lands on Hoover's shoulder. Then the other half. Piecing them together, Hoover realises he "loves this stuff. Edgar Jedgar, admit it – you love it. It causes a bristling of his body hair ... The meat blood colors and massed bodies, this is a census taking of

E-mail address: tbarnes@geog.ubc.ca

0016-7185/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.geoforum.2007.09.006

awful ways to die" (DeLillo, 1997, p. 50). Bruegel's image has special resonance because Hoover was just told that the Soviets tested a nuclear warhead at the Kazakh test site in Central Asia that same afternoon. At 3:58 pm, "the shot heard around the world." Bobby Thompson tomahawks a high and tight fastball deep into left field. Andy Pafko races, but the ball clears the back wall. "Giants win the pennant, Giants win the pennant, Giants win the pennant," bawls Russ Hodges the play-by-play man for KMOX radio (DeLillo, 1997, pp. 42–43). Hoover, though, with Bruegel in hand, thinks about only the other shot, the

> ... lonely tower standing on the Kazakh Test Site, the tower armed with the bomb, and he can almost hear the wind blowing across the Central Asian steppes, out where the enemy lives in long coats and fur caps ... This is what he knows, the genius of the bomb is not only printed in its physics of particles and rays but in the occasion it creates for new secrets. For every atmospheric blast, ... he reckons a hundred plots go underground, to spawn and skein (DeLillo, 1997, pp. 50–51).

This paper is about some of those plots that spawn and skein. They are not the usual Cold War intrigues involving Checkpoint Charley, spies coming in from the cold, and martinis stirred but not shaken. They are more mundane, but just as intoxicating. They are plots enfolded within mathematical models. For mathematical models became prime vehicles for prosecuting US military objectives, for prosecuting the Cold War. At RAND, undoubtedly the epicentre of mathematical modelling during the 1950s, whole continents and the world itself were routinely obliterated and put back together again Humpty-Dumpty-like, one simulation model of nuclear Armageddon after another. Mathematical models allowed thinking the unthinkable. Written by academics, encrypted in the cipher of Greek symbols, funded under the auspices of one military or quasi-military organisation acronym or another (RAND stands for Research ANd Development, although critics said Research And No Development), the models were "SECRET" and "CONFIDENTIAL."

My argument is that the mathematical models of the 1950s, like the bomb itself, are part of a much wider set of transformations stemming from the Second World War and extending into the Cold War. Just as the bomb is more than "its physics of particles and rays," mathematical models are more than Greek letters. The sociologist of science, Pickering (1995a, p. 5), following Michel Foucault's vocabulary for marking off abrupt discontinuous epochs, applies the term World War II regime to understand this period. It is a regime marked by disciplinary and material transgression, by what Pickering also calls cyborg history. From World War II onwards, ideas, techniques, machines, academic subjects, and institutions were brought together in combinations that never existed before, undermining old boundaries, creating new hybrids. Central to this re-jigging was mathematical modelling, as well as the machine that made its widespread practice possible. Cohen (1988, pp. 135–136) reckons the first computer in the US, The Electronic Numerical Integrator and Computer (ENIAC), in the ten years that it did military service in modelling ballistics, carried out more "arithmetic than had been done by the whole human race prior to 1945."

The mathematical models that entered geography for the first time from the 1950s were constitutively part of this larger World War II regime. Further, they were not mere atmospheric responses to developments happening elsewhere, but were brought about by specific individuals in the thick of the action, living within, and living out that regime. Individuals critical to pioneering modelling in various parts of the discipline – I focus on Waldo Tobler in cartography and later GIS, William Garrison in human geography, Arthur Strahler in physical geography – not only produced a different kind of geography, but also contributed to the very character and maintenance of the regime itself.

The paper is divided into three sections. First, I review some of the philosophical literature on models. There has been an important shift over the last few decades. Rather than models interpreted as disguised theoretical truths, models are viewed as agents in themselves, with power not only to represent the world but to intervene and to change it. This was exactly the case for the Cold War models at the centre of my discussion. Second, I provide a brief history and description of the larger character of the World War II regime, focussing on the role of mathematical modelling and its place within this cyborg period. Finally, I provide my three case studies of the interaction of geography with the World War II regime by examining the lives and works of Waldo Tobler, William Garrison, and Arthur Strahler. Each provided new geographical models, as well as a new model for geography.

2. Modelling models

2.1. The received view

In the syntactical view found within the Received View or Covering Law philosophy of science, models were ultimately regarded as superfluous, adding nothing to the crown jewels of scientific explanation: axioms, laws and theories. The classic statement was by the mathematical logician, Alfred Tarski: "A possible realisation in which all valid sentences of a theory T are satisfied is called a model of T" (quoted in Suppes, 1961, p. 163). For Tarski, and other upholders of the Received View, a model was an entity (a set of "sentences") that possessed the same deductive structure as the theory to which it corresponded. If it possessed a different structure, it was no longer a model of that theory. Logical isomorphism was key. For this reason, models did not add to explanation, but were merely parasitic upon existing axioms, laws and theories. As Newton da Costa and French (2000, p. S117) put it in their review, "at best, [models within the Received View] have an aesthetic, didactic, or heuristic value, but are 'quite unnecessary' when it comes to understanding or successfully applying a theory."

Necessarily, then, the Received View underplayed the role of models, consigning them to minor walk-on roles. In the history of geography over the last fifty years, though, both human and physical, models have been star actors, often at the centre of the action. Writing in 1969, Harvey (1969, p. 168) wrote, "The employment of models is the *sine qua non* for the progress and application of geographic research." Geography was not alone. Think of economics, a discipline in its post-war incarnation defined by its use of models. The economist Paul Krugman says, "To be taken seriously an idea has to be *something you can model*" (Krugman, 1995, p. 5, emphasis in the original). Or think again of the tumultuous changes in biology since Francis Crick and James Watson's construction of the DNA model. The historian of biology Kay (2000, p. 5) says, "In the postwar world order material, discursive and social practices of molecular biology were transformed." Biology became increasing mathematical, and computer based, focussed on genetic models. Further, in each of these three cases – geography, economics, and biology – we find Cold War cyborg connections. The common mid-century turn towards modelling was not mere happenstance, but associated with the larger epochal change of the World War II regime, and to which each discipline contributed (and discussed in the next section).

The reason the Received View underestimated the importance of models and the context of their deployment was because it ignored scientific practice. As a philosophical system, it was couched in terms of what scientists should do, and not what they actually did. Scientific explanation in the Received View consisted of a logically derived abstract, syntactical system of discrete, atemporal definitions, rules, and relations. Its truth existed in and of the system itself, not requiring human performance. But as Ernan McMullin (1968, p. 390) wrote in an early criticism of the Received View of models, "the logician leaves aside the temporal dimension of scientific procedures."

2.2. Modelling practice

Over the last 40 years philosophers and increasingly sociologists of scientists have striven to understand precisely those "temporal dimensions of scientific procedures," that is, scientific practice. What emerges, and seen in the quotations above, is recognition of the pivotal role of models. They turn out not be bit players, but constantly in the limelight; not surplus conceptual baggage, but basic necessities. With this realisation has gone significant re-conceptualisation of models and modelling.

Thomas Kuhn's work in *The Structure of Scientific Revolutions* (1962) was catalytic. Significantly, the book itself, as Fuller (2000) argues, emerged exactly from a Cold War context. Kuhn was a TA for the legendary "Nat Sci 4" course concerned with scientific "tactics and strategies" offered by the President of Harvard, and one of America's key post-war science managers, James Conant (and the man who closed Harvard's geography department). Conant introduced Kuhn to the history of science, and hired him to teach the course that became *The Structure of Scientific Revolutions*. Kuhn viewed models as the bread and butter of everyday problem solving within normal science. It is what scientists did after they got up each morning and went to work. Furthermore, and this is the important point, applying models always involved practice. Models were not defined by some far-flung corner of logical space, but represented material, embodied, and conceptual accomplishments in real time. Modelling took training, skill, instrumentation, creativity, and craft. Modelling was a hands-on achievement.

Hesse (1966) writing after *The Structure of Scientific Revolutions* offered a more radical proposal. She argued modelling is based on metaphorical re-description: applying concepts, methods, equations, and solutions in one field to a completely different one. There are shades of this view in Kuhn's writings in which he points to the importance of "exemplars" in solving puzzles, but exemplars for him were canonical texts and Ur-experimental techniques not metaphors as such.

For Hesse, however, metaphorical re-description could redefine a field. Models were not simply a means for problem solving within an existing paradigm, but potentially produced wholesale change. With Michael Arib, Hesse writes, "To make explicit the ramifications of metaphor is to engage in critique, evaluation, and perhaps replacement. Metaphor is potentially revolutionary" (Arib and Hesse, 1986, p. 156). This is the case in geography, economics, and biology. The history of each discipline is one of intermittent punctuation (some more intermittent than others) by abrupt and forceful metaphorical re-descriptions of its models, making the disciplines swerve and change course. Metaphorically re-describing the force of interaction between the populations of cities as the force of gravity between planets introduced geography in the 1950s to the very idea of mathematical modelling that burgeoned for a period into a hegemonic spatial science. Metaphorically re-describing the maximisation of consumer utility within an atomistic market in terms of an equation for the path of least effort of a particle's movement sparked rational-choice economic models, which subsequently defined the face of modern economics (Mirowski, 2002). And metaphorically re-describing the sequence of protein molecules in DNA as a secret code requiring decryption gave rise to genetic models, allowing the Book of Life to be read (Kay, 2000).

Models for Hesse possess independence, and agency. They do not simply describe the world, or help explain it (although they do both), but they also intervene, changing it. Certainly, disciplines are altered, but more widely so is the world. The gravity model was used to change urban infrastructures and services on the ground. The rational choice model justified Jeffrey Sach's shock therapy for Russia, structural adjustment policies in the third world, and

George Bush's $1.6 trillion dollar tax cut. And the genetic model produced Dolly the sheep, Monsanto, and the drug, Rebif, I inject myself three times a week to stabilise my MS. Models produce material effects, good and bad, big and small.

2.3. A new view of models

More recently, the arguments presented by Kuhn and Hesse have been systematised and extended by a group of contemporary writers keen to think through modelling outside the box of the received view.

First, unlike in the Received View, models are taken as autonomous. They are neither a thinly disguised version of empirical data, nor are they "theory-lite." They stand on their own feet as "autonomous agents" (Morrison and Morgan, 1999, p. 10). They are active mediators rather than passively submitting to data or passively submitting to theory. That models are not just souped up versions of data is clear in that their components are at best empirical approximations, and at worst, pure fictions. Cartwright (1983, p. 153) says bluntly, "A model is a work of fiction. Some properties ascribed to objects will be germane properties ... but others will be merely properties of convenience." Similarly, models do not reduce to the skeletal calculus of theory, and may well survive even when the associated theory is discarded. Hacking (1983, p. 217) writes, "models tend to be robust under theory change, that is you keep the model and dump the theory. There is more local truth in the inconsistent models than in the most high-brow theories."

For both Cartwright and Hacking the world is fundamentally messy, discontinuous, and contradictory. Pure laws and unblemished theories have only been derived in extraordinarily regulated settings, "primarily inside [various kinds of] walls ... within which conditions can be arranged *just so*" (Cartwright, 1999, p. 2). For the most part, our world is not like that. For Cartwright (1999, p. 1) it is "dappled world, a world rich in different things, with different natures, behaving in different ways." While for Hacking (1983, p. 219), "God did not write a Book of Nature ... [but] a Borgesian library, each book of which is as brief as possible, yet each book of which is inconsistent with every other." Models for Cartwright and Hacking, as well as Morrison and Morgan, are the mediators between the dappled world, the Borgesian library, and the regulated, engineered world described by laws and theory. That word mediator is important; it is not the same as conduit or reflection or mirror. Models are separate constructions, moving between, translating, arbitrating, and interceding in differences between the two worlds, and in so doing, making sense of them. They have a life of their own, lying somewhere between diverse phenomenological descriptions and unified formal theory.

Second, in fulfilling the role of autonomous constructions, models are assembled from a variety of elements. They are not minimal sentences of unsullied logic. Rather, and after Lévi-Strauss (1966), models are the product of the *bricoleaur,* not the engineer. Models are *bricolage*, crafted from disparate, and often quite distinct set of codes, signs, and texts, both tacit knowledge and formal knowledge. Bits of theory, the odd metaphor, lines of equations, a sprinkling of numerical data, an intuitive hunch, a few stylised facts, mandated institutional prescriptions, pieces of hardware, the whims of mathematical fashion, and more besides. van der Bogaard (1999, p. 323) says, a model has "to be understood in terms of a network that connects all kinds of heterogeneous aspects." Only once the parts are assembled, integrated, and are made to work together, is the justification made (Boumans, 1999).

Mathematics functions here as a glue for the model's disparate elements. This idea comes from Latour (1987, pp. 237–243) who speaks of making connections among heterogeneous elements in terms of "translation" by which he means combining, linking, and relating elements even though they are radically different. This is what equations do: "equations are *sub-sets of translations*, and should be studied like all other translations.... The web of association ... is *drawn together* by equations" (Latour, 1987, pp. 238–240). Equations by their very construction tie different things together, making the components represented equivalent. This is the aim of a model. By aligning, joining, shuffling, and relating a model's sundry components, mathematics fulfils that goal. Mathematical structures are useful not because they are Nature's own language as Galileo said, but because they "serve as multi-purpose translation devices, making connections among diverse cultural elements" (Pickering, 1995b, p. 422).

Third, models, as Morrison and Morgan (1999, p. 11) write, "function as tools or instruments ...; and like tools, they can often be used for many different tasks." In this sense, models are a form of technology, analogous to machines that intervene in the world, allowing us to cope with variety and messiness. As a technology, models are useful in two main respects. They are instruments to think about the world, and instruments to alter it.

Thinking about the world clearly includes its representation, but it need not be confined to that function. MacKenzie (2003, p. 858) in examining models of derivative trading on financial markets says they serve as "resources ... ways of understanding and reasoning about economic processes, not [simply] putative descriptions of reality." What he means is that a model such as formulated by the economists Black, Merton, and Scholes, and which won the authors a Nobel prize, enabled the economy to be conceived in new terms, changing that very object. Their model portrayed a form of trading that did not yet exist; it imagined a future that became a reality; the model produced the reality. Or another example, more germane to the paper, were computer simulation models of Cold War futures. Edwards (1996, p. 169) writes, "To a very large degree the Cold War was actually prosecuted through simulations... [It] was fought inside a quintessentially semiotic space, existing in models, language, iconography, and metaphor, and embodied in technologies which lent to the semiotic dimensions their heavily inertial mass."

As instruments, models also change the world, they instrumentally intervene. For example, hydrological models used by the US Army Corps of Engineers to stem (or not) the flooding of the Mississippi River. But there is also another sense in which models intervene which is when the world is changed in order to realise the logic of the model. The Black, Merton, and Scholes model is the perfect example. New markets, associated with new kinds of traders, with new expertise, and the hardware necessary for its execution, emerged in international financial centres in order to satisfy the equations of the model. The same applies to Cold War models. America was materially changed such that it accorded with a war fought only in semiotic model space. As Edwards (1996, p. 169) writes again, "Each [military] service based its weapons purchase, force deployments, technological R&D, and negotiation postures on its models of strategic conflict and its projections about the future choices of the other."

Finally, models are historically contingent, constructed in real time, and open-ended. Because they are *bricolage*, instruments for particular purposes, and produced in the brouhaha of on-going scientific practice, models necessarily reflect the historical and geographical moment. Pickering's (1995c) work is especially useful, portraying science, including modelling, in terms of the "mangle of practice," defined as "the continually ongoing, open-ended transformation of mutually interactive cultural elements" (1995d, p. 475). For him, the world and how to make sense of it are continually in motion, churning, intermingling, becoming. Pickering (1995c, p. 6) writes:

> The world is filled not, in the first instance, with facts and observations, but with agency. The world is continually doing things that bear upon us not as observation statements about disembodied intellects but forces upon material beings ... We should see science ... as ... the business of coping with material agency.

For Pickering science copes with material agency by mobilising various material or conceptual resources. These resources include models. Models are a means to enter and to deal with the world's material agency. Agents in their own right, models engage in what Pickering (1995b, p. 443) calls a "dance of ... agency," or in other places "a dialectic of resistance and accommodation" (Pickering, 1995c, p. xi) That is, models attempt to cope with the world, to try to get involved, to get a fix on it. But that world is constantly shifting, moving outside the grasp of the model, asserting its own agency. For this reason, modelling is always a contingent, "open-ended process with no determinate destination" (Pickering, 1995c, p. 20). The model makes one move, the world modelled makes another. There is never final resolution, only a ceaseless dance, only the rolling drums of the mangle.

While such transformations are continuous and contingent, some transformations are more significant, more far-reaching, producing longer-term consequences than others. Pickering singles out World War II as one of them, and which continued into the Cold War. As a contingent event, the Second World War entered the mangle like any other, but the resulting transformations, "dances of agency," "dialectics of resistance and accommodation," were profound, not minor. The very project and practice of science, and social science for that matter, were reconstituted as the mangle did its work. Science and social science emerged at the other end at least in the United States as increasingly cyborg forms of enquiry, tethered to the computer, and ones in which mathematical models were central. Further, such models were not the weak, conceptually thin, passive, and purely logical kind formulated by the Received View, but robustly autonomous, multiply constituted, actively instrumental, and historically embedded. They changed the world, and along the way, they changed the discipline of geography.

3. World War II, the Cold War, and models

What changed the world was the bomb. It is present at the bottom of the ninth in that last game of the National League pennant race in 1951, and continues to be present long after, maybe forever. For my purposes, even more interesting are the conditions required to make the bomb. Deleuze and Parnet (1987, p. 96) say, "You cannot grasp or conceive of a desire outside a determinate assemblage, on a plane which is not pre-existent but which itself must be constructed ... Every assemblage expresses and creates a desire by constructing the plane which makes it possible, and by making it possible brings it about." I am concerned in this section with understanding the historical process by which the plane of the World War II regime was constructed, and which brings about the bomb's possibility and then its existence. But, and this is the real point for this paper, it is not only the bomb that is constructed. A whole assemblage is required, and which as I will argue includes among its elements mathematical modelling, not only in the sciences but the social sciences too. After the bomb is built, and even dropped, the assemblage remains. War continues.

3.1. Wartime mangling

In Pickering's terms the outbreak of World War II produced "mangling" between the sciences (including the social sciences) and the military. Forced by Presidential order, eased by large sums of money, and coaxed by various institutions such as the Office of Scientific Research and Development (OSRD) and the Office of Strategic Services (OSS), science, social science, and the military engaged one another.

The process began even before the United States entered the War. As early as June 1940, President Roosevelt established the National Defence Research Committee (NDRC), initially under the direction of Vannevar Bush, formerly Vice President of MIT, with the mandate "to coordinate, supervise, and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare" (quoted by Cochrane 1978, pp. 391–392). The NDRC supervised the Manhattan Project, although after June 1941 it was headed by Harvard President James Conant, in his earlier life a professor of chemistry who developed poisonous gas. Bush had become head of the even more powerful OSRD that by war's end operated with a budget of $450m. The money was narrowly distributed for weapons research either to a handful of elite universities – not surprising MIT, and especially the Radiation Laboratory (RadLab) housed at Bush's former Engineering Faculty, received the lion's share (35% of total OCRD's funding) – or to private companies.

Such mangling did not happen only to the sciences, but the social sciences as well. In July 1941, President Roosevelt signed an executive order creating the Office for the Co-ordination of Information (OCI), which in the following year became the Office of Strategic Services (OSS), and forerunner of the Central Intelligence Agency (created in 1947). The OSS, and in particular, its Research and Analysis branch (R&A) headed by the Harvard European historian William L. Langer, was in the business of the accumulation, analysis and interpretation of knowledge by the social sciences for strategic military ends. The results were not quite as spectacular as in science. But R&A certainly influenced military strategy just like the physical scientists (Barnes, 2006).

In addition, lying between science and the social sciences was Operations Research (OR). The origins of OR are British. It emerged in the mid-1930s associated with the Tizard Committee on Air Defence, but was more systematically developed once war began. Called in the UK "operations analysis," Patrick Blackett's "Circus" consisted of three physiologists, four physicists, two mathematicians, and one surveyor, and developed mathematical techniques and models to optimise the use of radar to aim anti-aircraft guns. Once across the Atlantic, the remit of Operations Research, as it was re-dubbed, was generalised, and it became the repository for mathematical methods and techniques for best facilitating the Command, Control, Communications and Information (C^3I) function of the Armed Forces and which bore on everything from the logistics of supply boat arrival to constructing battlefield tactics. OR was defined by its capacity less to invent something new than to realise specific objectives using mathematical models, and which came to include game theory, Monte Carlo simulation models, linear programming, markov chains, network analysis, queuing theory, and cost-benefit analysis. The hallmarks of these various techniques were their "ability to make arguments rigorous through the instrumentality of formal expression" (Mirowski, 2002, p. 180). A bastardised descendent of Taylorism, OR was also the personification of Pickering's cyborg history, falling betwixt and between science and social sciences, and linking physicists, mathematicians, engineers, economists, planners, and, as we shall see, even the odd geographer.

As this was going on, the military was changing. This was the nature of the mangle. All parties were altered. The inventions of new devices like, of course, the bomb itself, transformed military tactics, modifying the very conception of conflict and war. The military and the sciences were enfolding on to one another in novel, and hitherto unimagined combinations, creating an original assemblage. Pickering (1995b, p. 18) writes: "What had been largely separate and autonomous institutions before World War II ... had been profoundly transformed and locked together as a complex, social, material, and conceptual cyborg entity by the end of it."

The nature of that assemblage emphasised a pragmatic, instrumental view of knowledge. It was less concerned with theory than with constructing tools to intervene, and was accomplished using material technology, and the technology of models. It was less concerned with disciplinary divides than bringing together expertise from wherever it was found, joining, overlapping, connecting, creating cyborg forms, creating *bricolage*. Interdisciplinary team-based research consequently was the norm whether at the RadLab, OSS, or at Blackett's Circus. It emphasised formal reasoning, rationality, deductive logic, allowing connections to be made across heterogeneous entities, and heterogeneous practitioners. And it was an assemblage predicated on the belief that large sums of money and resources were the means to solve problems, whether building the Bomb, or knowing how to bomb. Those problems were not given in advance, but emerged in real-time, thrown up by the contingencies of warfare, and embedded in the moment.

3.2. Cold War cyborg science

The assemblage became even more solidified and entrenched once the war finished, and the Cold War began. For it had delivered the goods: it produced victory. Dwight Eisenhower, then Army Chief of Staff, said in 1946:

> The lessons of the last war are clear. The military effort required for victory threw upon the Army an unprecedented range of responsibilities, many of which were effectively discharged only through the invaluable assistance supplied by our cumulative resources in the natural and social sciences and the talents and experiences furnished by management and science ... This pattern of integration must be translated into a peacetime counterpart ... (quoted in Allison, 1985, p. 290).

It was. What emerged, and was to become fully formed during the Cold War, was a "military–industrial–academic complex," as Senator William J. Fulbright later labelled it (Leslie, 1993). Parts of society hitherto separate and independent – the armed forces, corporations, and universities – were joined and integrated. They were mangled, continuing the cyborg history.

At least initially, the military were key providers of funds, although this changed through the course of the 1950s as non-profits became more numerous, and federally funded research schemes were inaugurated. That said, during the 1950s, 80% of Federal US R&D expenditure still derived from the Department of Defense (Leslie, 1993, p. 2). For the social sciences, the Office of Naval Research was especially important, and it was not until 1958 that the bulk of social sciences were covered under the financial mantle of the National Science Foundation. Consequently, as Kay (2000, p. 77) writes, "military patronage was not simply a resource external to the scientists' projects ... Rather the web of military institutions sponsoring scientific research defined the conditions of possibility for the production of particular forms of knowledge."

Associated with the distribution of the money was a new breed of science managers. They were the usual suspects, however, those who administered military research during the War, and included James Conant and Vannevar Bush, and the man with his finger in every pie, the émigré Nobel-prize winning scientist, John von Neumann. Universities, or at least select universities, were recipients of this military money. But other institutions gained too, particularly non-profits of which the most well known was RAND based in Santa Monica, California.

When founded in December 1945 within the Douglas Aircraft Company, RAND reported to the Army Air Force. By 1948, it was a separate non-profit organisation, still tied closely to the newly created United States Air Force, concerned with providing interdisciplinary information and knowledge to the military (Hounshell, 1997; Collins, 2002). Its hallmark pursuits turned on mathematical modelling, and particularly the use and development of OR techniques. Arthur Raymond, one of the first directors, said, "Questions ... of the various social sciences ... are not omitted [at RAND] because we all feel that they are extremely important in the conduct of warfare" (quoted in Jardini, 2000, p. 315). RAND established graduate fellowships, offered defence policy seminars at Ivy League universities, and, at Santa Monica, it brought together a who's who of American scientists and social sciences to work on a variety of problems turning on the "science of warfare" (Hounshell, 1997, p. 244). Those employed by RAND included von Neumann, the economists Kenneth Arrow and Tjalling Koopmans (both later winners of the Nobel Prize), the man with the "beautiful mind," another Nobel prize winner, John Nash, the analytical philosopher Hans Reichenbach and *Time*'s cover boy for the organisation in 1959, and (at the Systems Development Corporation, a RAND spin-off), Waldo Tobler, who worked on a project to develop a computer-based early warning system for nuclear attack (SAGE) (discussed further below).

Increasingly central to the work at RAND, and more generally, to the kind of knowledge that was produced by the Cold War assemblage was the computer. The first semi-programmable computer, the Colossus, was developed for military purposes at Bletchley Park, and used by the British to crack the German Enigma code. In the United States, von Neumann as both über genius and über science manager propelled the computer's development after the war. The Moore School at the University of Pennsylvania had been under contract from 1943 to develop ENIAC for ballistic testing for Army Ordinance. In August 1944, von Neumann serendipitously met the head of that project, Herman Goldstine, on the railway platform at Aberdeen, Maryland, home to the Ballistics Research Laboratory. The rest was history. Von Neumann helped design the next generation of computers, the EDVAC, and at the same time outlined the blueprint for the electronic storage of programmes. The first electronic stored programme computer went to Los Alamos in 1953, and appropriately enough, RAND received in the same year the JOHNNIAC computer, named after von Neumann. By the end of the decade, RAND had more computing power than any single site in the world, and even State Universities could boast ownership of one numbered IBM computer or another. By today's standards, they were lumbering dinosaurs, but even then they could perform calculations with a speed, consistency, and stamina that no human could match, and vital to the project of modelling.

3.3. Cold War models

That project became increasingly central to the Cold War, entering its purpose and form. Following the arguments in Section 2.3, models were important to the World War II regime because first, they were autonomous of both high theory and phenomenological description. The assemblage created was not any motley of elements, but carefully organised to fulfil a particular end: to win a war. The regime was not interested in pure theory, in conditions arranged "just so." Testing the nuclear bomb was not a laboratory experiment to investigate the structure of the atom. Its test conditions were not arranged "just so." In fact, Enrico Fermi was sufficiently uncertain about the outcome that he made side bets at the Trinity test site as to whether the explosion would ignite the atmosphere and incinerate either New Mexico or the entire Earth. At the same time, the very rationale of the assemblage, of linking science, and at least certain brands of social science, with the military, was to go beyond listing of the facts. The sciences offered though their rigour, analytical purchase, and generalisations, the means to exceed mere description. Models lay exactly between the worlds of high theory and empiricism to which the World War II regime aspired. Models were mediators, and consequently seized upon.

Second, as a form of *bricolage*, models could connect and incorporate within their very architecture, the disparate elements of the World War II regime. This was the central problem: to gather up and bring together the heterogeneity of the cyborg form. Models provided a solution. Models are not like theories, reducible to a small set of precisely defined terms, operating in "just-so" conditions. They possess a give and flexibility, an expansiveness, a made-on-the-fly quality that can incorporate difference, connect diverse components. Let me provide an example, the development of linear programming models that began after World War II, and discussed by Mirowski (2002, pp. 249–262). Developed by Tjalling Koopmans, linear programming combined: (1) mathematical techniques Koopmans first learnt in physics and statistics and in which he was originally trained; (2) metaphorical redescription of the shipping route problem that Koopmans first encountered during the War at the Shipping Adjustment Board in Washington, DC, and which he applied to allocation issues of first the military and later civil society; (3) the logistical demands of the military C^3I structure in which market-based allocation was not possible and therefore required an alternative mechanism of resource distribution; (4) the need by the Cowles Commission that Koopmans headed for a central technique or product that could attract institutional funding (in this case, from RAND); (5) linkages to other OR techniques also emerging, particularly, Morgenstern and von Neumann's game theory; and (6) a disposition for machinic numerical solution the means for which were at that very moment being constructed by von Neumann and his colleagues. Linear programming models may not be a Borgesian library but they speak to many worlds, not one. No wonder Koopmans won the Nobel prize for his work on linear programming given its ability to connect so many interests.

Facilitating those diverse connections was formal reasoning. To use Latour's metaphors, mathematics enabled connections to be made from diverse origins in the same way as a "digital telephone exchange" or a "cloverleaf highway intersection" (Latour, 1987, p. 242). Someone like Koopmans given his prior training was well positioned to deploy mathematics in the models he developed to make possible that end. Many other social scientists were not. But they had little option. This was to be the new way of the world. Carl Schorske characterises the development of the human sciences during the period 1940–1960 as a "passage ... from range to rigor, from loose engagement with a multifaceted reality historically perceived to the creation of sharp analytical tools that could promise certainty where description and speculative explication had prevailed before" (Schorske, 1997, p. 295). Key to the "new rigorism" that Schorske describes was mathematical models. To that end, in 1952 the Social Science Research Council formed a Committee on the Mathematical Training of Social Scientists, which was subsequently mirrored in the establishment for individual disciplines of a plethora of summer schools, faculty seminars, and training camps in quantitative methods. The first one in geography was in the summer of 1961 at Northwestern University, Evanston, Illinois, and organised by Brian Berry and Ned Taaffe (Barnes, 2004).

Third, Cold War models perhaps above all else, were instruments of intervention, the means to achieve specific ends. Again, this goes to the very core of the World War II regime. It was directed to an overriding pragmatic objective, to beat an enemy. The elements of the assemblage were exactly arranged to fulfil that purpose, including its models. First, they facilitated thinking about conflict before it happened, enabling preparation and strategy. Key were simulation models of the kind already discussed. Mirowski (2002, p. 15) writes, "The entire Cold War military technological trajectory was based on simulations, from the psychology of the enlisted men turning the keys to the patterns of targeting of weapons to their physical explosion profile to the radiation cross section to anticipated technological improvements in weapons to the behaviour of the opponents in the Kremlin to econometric models of a postnuclear world." The models were not yet of the world, but they helped the military think about a world that might be, and thus the conditions necessary to make it a reality if necessary. Second, models intervened materially in the world, changing it in such ways as to make victory more likely. This is trivially true for models used, say, at the ballistic testing site at Aberdeen that made armaments more accurate. But models also changed the world by making the world mirror the model. Cold War America was materially changed to accord with a war fought in the spaces of simulation models. Edwards (1996, p. 169) writes, "Each [military] service based its weapons purchase, force deployments, technological R&D, and negotiation postures on its models of strategic conflict and its projections about the future choices of the other." Models were not pallid reflections of the world, but a full-bodied means to change it.

Finally, Cold War models were historically contingent, fabricated in real time, and always open to revision, including their excision. This is the very meaning of the mangle. As new elements enter, there is adjustment all around. For example, the Soviets now have the bomb, as they did from 1949, better change the assumptions of game theory. The Soviets now have Intercontinental Ballistic Missiles, better rethink air defence strategy, and implement other plans like population dispersal (although still regulated by models; Edwards, 1996). There is one other aspect of the local character of models, their embeddedness in ideological interests. From the Soviet view, Western scholarship, and American scholarship in particular, was corrupt and perverted. In 1952, the Soviet Academy of Sciences Institute of Philosophy, promised to "criticize and destroy all reactionary philosophical trends that appear in bourgeois countries under new, modish names" (quoted Gerovitch, 2001, p. 257). Presumably, that included new, modish models. They were the product of the capitalist ideology of science, but which were to be avoided under the Communist regime (Gerovitch, 2001). Indeed, the use of mathematics particularly in economic planning was viewed as dangerous (and mortally so in the case of Nikolai Kondratiev, the mathematical and statistical economist and model builder executed by Stalin in 1938 at the Moscow trials).

In a 1971 issue of Science, Deutsche et al. (1971) ranked the 62 most significant advances in the social sciences for the period 1900–1965. At least a quarter of the advances listed were mathematical models associated with the Second World War, and the Cold War, and included favourites like game theory (ranked 31), linear programming (ranked 43), operations research and systems analysis (ranked 47), and computer simulation models of social and political systems (ranked 60). While the scheme is easy to criticise, it indicates the importance of mathematical models during the period of the World War II regime. Certainly, as a mentality they came to dominate certain disciplines. Economics is perhaps the best example (Bernstein, 1995; Mirowski, 2002). But economics wasn't the only social science influenced by mathematical modelling, and clear from Deutsche et al.'s listing. Psychology, sociology, political science, and even philosophy were caught up either directly or indirectly in the same move, pushing those disciplines into the top 62. I would like to make the argument now that geography was carried along on that same trajectory, even though it is conspicuously absent on Deutsche et al.'s list.

4. Geography's Cold War modellers: three examples

Geography does not make it into the top 62 because during much of its history in the first 65 years of the twentieth century it was atheoretical, was not mathematical, and did not do scientific models. That said, most geographers during this period still considered themselves scientists, but science after natural history involving fieldwork, detailed description, scrupulously recorded observations of a lone scholar, and a tendency towards classification, even the encyclopaedic. Precisely this approach to science was canonised in American geography by Hartshorne (1939) in *The Nature of Geography*, published ironically just as the World War II regime was about to begin (Barnes and Farish, 2006). Partly because of Hartshorne's immediate post-war influence, partly because of the weight of past intellectual tradition, American geography initially held off being pulled into the mangle. But the mangle's rollers continued to spin, and as they did, eventually some geographers and geographical ideas were pulled in. Consequently, mathematical models of various kinds were turned out on the other side.

4.1. Waldo Tobler, SAGE, and automated cartography

Waldo Tobler was pulled in. In 1957, he found himself inside the whale, living in Santa Monica, working for a spin-off of RAND, the Systems Development Corporation (SDC). His job was to "assist in the preparation of computer printed maps used in air defense simulation exercises" (Tobler, 2002, p. 304).

His job existed because of SAGE (Semi-Automated Ground Environment). SAGE was the personification of the military–industrial–academic complex, cyborg history, in this case, the enfolding of the US Air Force and Navy, IBM, and MIT, along with the non-profit, RAND. On August 29th 1949, the Russians successfully tested its first nuclear bomb, and beginning "the long twilight struggle" as President Kennedy called it. For the US military, the issue was how to prevent a knock-out blow, Soviet nuclear first strike. SAGE was the answer, an automated tracking system combining radar and the latest advances in computer technology (reviewed thoroughly in Edwards, 1996, and especially Hughes, 1998). As Edwards (1996, p. 94) writes: SAGE represented "a grand scale plan for national perimeter air defense controlled by central digital computers that would automatically monitor radars on a sectoral basis. In the event of a Soviet bomber attack, they would assign interceptors to each incoming plane and co-ordinate the defensive response. The computers would do everything from directing an attack to issuing orders . . . to interceptor pilots."

MIT was a natural home for SAGE. Radar had already been extensively developed at its RadLab during the War. Further, MIT's Electrical Engineering Department was prominent in computer research. Vannevar Bush as a faculty member had invented in 1927 the differential analyser, an analogue computer that could solve differential equations with up to 18 independent variables. In the late 1940s, it was the young faculty member, Jay Forrester, who was up and coming. Following Wiener's (1961 [1948]) vision of cybernetics, Forrester envisaged a digital computer not simply as a mechanical calculator, but capable of automatically making decisions based upon changing information. Project Whirlwind, headed by Forrester, funded initially by ONR, and carried out in a specially constructed MIT laboratory, the Lincoln Lab in New Bedford, MA, was the result. It would be the digital computer forming the backbone of SAGE. Envisioning a project lasting 15 years, with a budget of $2 billion (the combined cost of the Manhattan Project and the RadLab), Forrester's group developed many of the features that continue to characterise contemporary computing including networking, high-speed, real-time processing, time sharing, core memory, random access storage, digital data transmission over telephone lines, and cathode ray tube monitors. Added to this military–academic alliance, was the third leg, industry. In 1952, IBM was chosen as manufacturer of Whirlwind's computers. Each cost $30m, and at its height, their manufacture occupied 7000 IBM workers, 20% of the firm's workforce.

Where RAND, and ultimately Tobler enter the story, is around programming the computers. In a fateful decision, IBM decided it was not in the business of computer software. It expected programming to be a one-time shot. And so programming was subcontracted to RAND. It proved an enormous undertaking involving the writing of over a quarter of a million lines of integrated code, and preoccupying 800 programmers at its peak. In 1957, RAND spun off a subsidiary, SDC, to undertake the programming, and which quickly came to exceed RAND's size by fourfold.

1957 was also the year that Waldo Tobler finished his Masters Degree at the University of Washington, Seattle, having worked with the cartographer, John Sherman, and also having been exposed to mathematical modelling in William Garrison's seminars (discussed below). Just as importantly, he was exposed to the computer. In the attic of the Chemistry Building at the University of Washington Campus was the first university computer, an IBM 650, installed the year Tobler entered the Geography graduate programme in 1955. With access only during the early hours of the morning, Tobler engaged in then state-of-the-art programming. "With your best coding," Tobler (2002, p. 303) says, "you could get two pieces of data on one revolution of the ... 'huge' two thousand byte rotating storage drum." Tobler's graduate experience and training, in turn, made him a shoo-in for the SDC position he applied for once he graduated.

Tobler worked at SDC for a year, "generat[ing] graphics and plastic overlay templates for radar screens that were used in simulations for training radar operators to respond to emergency operations. Often the maps were manually generated, but the use of the Duplexed IBM 704 led to experiments with computer mapping and plotting directly" (Clarke and Cloud, 2000, p. 198). It was a formative experience. It influenced the topic of Tobler's Ph.D. thesis he later undertook again at Washington with John Sherman on map transforms, 1959–1961 (Clarke and Cloud, 2000, p. 198). It also led him to write in 1959 for the *Geographical Review*, "Automation and cartography" (Tobler, 1959). That paper was the first in geography to think through the possibilities of bringing together computers and cartography (although computer drawn maps had existed since 1951, and Tobler himself plotted computer generated maps from 1957). For Tobler the two formed a perfect match because once maps are "viewed as a complex data processing system, certain similarities then become apparent between data processing in general and cartographic processing in particular" (Tobler, 1959, p. 526). In particular, such a correspondence meant that just as high-speed computing machinery facilitated the automation of data processing, it could do the same for cartography.

With this connection made, Tobler (1976, 2000) began to develop what he was later to call analytical cartography. Making use of the computer, drawing upon formal mathematical methods, linking with spatial analysis, Tobler (1976, p. 22) "wished to emphasize ... that the objective [of analytical cartography] is the solution of concrete problems." This project was the correlative to the modelling that emerged in the social sciences during the same period. Couched in a formal vocabulary, dependent upon machines, analytical cartography lay between theory and empiricism, and was a potential means to modify the world and to represent it in new ways.

Because of the possibilities for military advantage, some of the work under analytical cartography at least for a period was kept secret and confidential. Tobler (1976, p. 21) in discussing the development of analytical cartography notes "the gap between official government cartography, and academic geographical cartography." Clarke and Cloud (2000) here use the metaphor of a shuttered box to address the fissure between what is allowed into the academic realm from military secret research and what must stay clandestine. As they write, "Academic cartography was necessarily playing catch-up ... with the advances of two decades worth of intensive, but deeply secret analytical cartography" (Clarke and Cloud, 2000, p. 196). The larger point, and brilliantly demonstrated in Cloud's (2002) subsequent research, is that the various components that made up Tobler's analytical cartography – and his 1976 paper even provided a course outline – were mired within the military–industrial–academic complex. Analytical cartography was just another of the things that emerged from the mangle of the World War II regime. And that mangle continued to revolve. For there is no final resting place, no determinate end point. Analytical cartography pressed out further change as it too was mangled. Clarke and Cloud (2000, p. 195) write, "analytical cartography is the sub-discipline of cartography that lies behind much of the development in geographic information science." And so, a new round or mangling that produced among other things, smart bombs, virtual battlefields, and electronic strategic battlefields. Tobler's work was not simply a product of the Cold War context, but entered back into it, changing its configuration, and shaping the military even after the Cold War was over.

4.2. William Garrison, highway construction, and models

Tobler attributed his 1957 appointment at SDC to "Professor Garrison [who] had encouraged us all [at the Department of Geography, University of Washington] to take mathematics courses and to learn to use the digital computer in addition to the mechanical desk calculator" (Tobler, 2002, p. 304). But why did he do that? Hartshorne (1955) still ruled in geography in 1955, and in fact, had just pulverised Schaefer (1953), even though Schaefer had been dead for two years, because he dared to offer a contrary position. What was Garrison thinking? His thinking had been mangled.

Garrison experienced the Second World War in a Flying Fortress in the Pacific Theatre. He enlisted in the US Air Force in 1942 as an aviation cadet, and attended a nine-month meteorology course. It was there that Garrison was exposed to higher-level mathematics including "a tough course in dynamic meteorology involving thermodynamics and fluid mechanics" (Garrison, 1998). At Northwestern University after the war as a graduate student in geography, however, Garrison returned to the Hartshornian tradition. So disgruntled was he with his resulting regional-geography based PhD dissertation that involved just "a lot of walking around, ... classification and description" (Garrison, 2002, p. 103), that he now says it was "the most fortunate thing that Northwestern University library lost it!" (Garrison, 1998). Hired in 1950 at the University of Washington, he was first exposed to Cold War money and science at the University of Pennsylvania's Wharton

School, where he spent the academic year 1952–1953. Assigned to Project "Big Ben," a classified Department of Defense venture, it led to interaction with economists, statisticians and biologists, a collaboration which "stimulated [his] imagination for analytic work," and the construction of models (Garrison, 2002, p. 105).

Both began shortly after he returned to Seattle. Serendipitously, a number of analytically inclined graduate students, later collectively dubbed the "space cadets," began arriving for graduate school at the Department the same time. The first, Duane Marble, entered the programme the year Garrison returned. In fact, that next summer he and Marble went to Stanford to attend a Summer School in Mathematics for Social Scientists organised by the Social Science Research Council. In 1955, another contingent of graduate students enrolled including Brian Berry, Ron Boyce, Richard Morrill, John Nystuen, and of course Tobler. It was that same year that Garrison gave the first ever statistics course in an American Geography Department, as well as two courses in location theory. And it was in 1955 that the IBM 650 was installed in the attic of the Chemistry Building.

The Washington group around Garrison defined itself by a model-based form of inquiry, later influencing the wider Anglo-American geographical community in what was called the "quantitative revolution" (Barnes, 2004). Partly those models came from OR, particularly, linear programming, partly from an allied contemporary movement, Regional Science, and partly from a reclaimed older German tradition of location theory. The models that were developed were mediators, cast between data and theory; made connections across heterogeneous sources by means of mathematical equations; were directed toward very specific interventions; and embedded within, and responsive to, historically specific events.

Those events, though, were not necessarily directly connected to war as such (although they could be). This marks an important change in modelling culture around especially what social science models could achieve. The Second World War and early Cold War indicated that joining social scientific theory with newly invented analytical techniques and empirical data in models could solve pressing practical military problems within a centralised command and control setting. By the late 1950s, it was increasingly believed that those same techniques could be used to solve practical problems within civil society, such as those faced by America's burgeoning post-war urban centres and regions, problems increasingly overseen and managed by a centralised state. RAND, for example, moved away during this period from direct links to the Air Force to a focus on issues of civil society (Hughes and Hughes, 2000, pp. 16–17). Jardini (2000) even suggests that the means to achieve Lyndon Johnson's "Great Society" were taken from the Pentagon and RAND. The point is that the usefulness of social scientific models was being reconceived, extended, and pushed into a new direction. Some of the funding sources were the old ones, ONR, in particular, but new sources were also emerging. Garrison and his students with their analytical techniques, savvy computer skills, grounding in mathematics, and exploration of models, were poised to enter this new game, to engage in strategic geographical intervention.

They did not wait long. In 1955, the Washington State Highway Commission contacted Robert Hennes and Edgar Horwood in Civil Engineering at the University of Washington to examine potential "user and nonuser benefits" resulting from construction of a highway system around Seattle (Garrison et al., 1959, p. v). There were both Cold War and non-Cold War imperatives operating. The Cold War one was to construct a means for Seattle residents to leave their city should the unimaginable happen. With SAGE, there would even be some warning time before Russian bombers dropped their payload. The non-Cold War one was the growing population of Seattle, and the freeway suburban planning model chosen to accommodate it. The project gained greater impetus when the Highway Revenue Act was passed the following year guaranteeing continued money. Financed for the first year at $30,000, Hennes and Horwood invited Garrison on to the project, along with other disciplinary representatives across campus.

Those disciplinary representatives were expected to toe the cyborg line, to use models and mathematical techniques to plan and organise "highway development ... within an entire social, political and economic system" (Garrison et al., 1959, p. vii). It was the perfect assignment for Garrison and the space cadets, allowing them to hone their analytical and modelling skills, to bootstrap-learn from other disciplines practising the "new rigorism" longer than geography, to bring the discipline in alignment with other Cold War social sciences, to show that geographers could make practical contributions without embarrassing themselves, and to be on the receiving end of Federal largesse. Garrison and his students produced what Morrill (1984, p. 61), one of the co-authors, called a "revolutionary book," *Studies of Highway Development and Geographic Change* (Garrison et al., 1959). It was revolutionary in that it introduced to the discipline a distilled dose of formal modelling. Stephen Enke's model of spatial separated markets was used to analyse physician utilisation at national, regional and local scales; Martin Beckman's model of transportation was used to predict demand for transportation at urban sites; Walter Christaller's model of central places was used to understand the spatial organisation of urban land use; Johann von Thünen's model was used to explain differences in urban rent; and Walter Isard's substitution model was used to evaluate the effects of transportation costs on the location of economic activities.

The result was a book that looked like none other that had ever been published in the name of geography. Crammed with calculations, data matrices, statistical techniques, cost curves and demand schedules, even the maps were subverted with the modelling mentality, overlaid with numbers, arrows, starburst lines, and balancing equations.

As odd as they may have looked in 1955, within ten years, the discipline had been changed such that they were the norm. In the interim, human geography radically altered, its disciplinary practices changed as modelling was performed. This was also another revolution. But as John Cloud suggests in the paper's epigraph, the route of the revolution had been laid out much earlier, the origins of which lay in the World War II regime.

4.3. Arthur Strahler, dynamic geomorphology, and ONR

Mark Felt as "deep throat" famously told Bob Woodward, "follow the money." This has been a strategy in Cold War science studies. Forman (1989, p. 150) in a now classic study showed that military research funding in physics from 1940 had caused "a qualitative change in its purpose and character." Arthur Strahler, the third case study, is someone who followed the money. This is true both personally in that he gave up academic research in 1968 to enter the lucrative world of textbook writing (or at least lucrative for some), and professionally. His research at the Department of Geology, Columbia University, during the Golden years 1950–1960, was funded by the military, primarily grants from the Office of Naval Research. It was money not just for him but also for his (later famous) students who included Dick Chorley, Mark Melton, Marie Morisawa, and Stanley Schumm, and who along with Strahler collectively helped to transform geomorphology into a natural science defined by mathematics and models.

Funding of earth science research by the military was pervasive during the Cold War period, generating an enormous amount of research, some parts secret other parts not, and at times changing the very research practices of scientists. Doel (2003, pp. 635–636) writes, "In the years immediately following World War II, the earth sciences expanded dramatically. Military patronage ... shaped the character and context of these fields, which may be termed the physical environmental sciences.... The most significant effect of military patronage was to create a new intellectual map for these disciplines." Those that most benefited dealt with aspects of the physical environment which most bore upon military operations and strategy such as oceanography, meteorology, seismology, soil science, and geology including geomorphology. They were recipients of "billions of dollars worth of funding and new technologies ..." (Cloud, 2003, p. 629).

Arthur Strahler as a geologist was engaged in one of the favoured earth sciences. While much of that funding came from the Research and Development Board at the Department of Defense, Strahler's financial support derived from the Office of Naval Research (ONR). ONR was established in 1946, and functioned as the principal vehicle for Federal research funds until the inauguration of NSF in 1950. But even after that date, it continued financially to back research projects partly because NSF was so miserly and restricted, at least until the late 1950s, and partly because there were some projects that were so directly related to military purposes they were irresistible (such as SAGE that hoovered up piles of ONR money). ONR was sub-divided into branches, one of which was geography. Geology was defined under physical geography, allowing Strahler access to ONR funds, and which the Branch Director, initially Louis O. Quam, and later Evelyn Pruitt ("always helpful and enthusiastic," Strahler, 1992, p. 71), was only too eager to provide. Strahler had nine PhD graduate students over the period 1950–1960. All of their research was funded by ONR.

Funding was forthcoming partly because the research was so directly on the physical environment, and partly because of its intellectual style. It conformed to the hallmarks of other Cold War sciences: mathematical, when necessary drawing upon the computer, use of models, occupying a position mid-way between high theory and recitation of facts, making links and integrating with a variety of other disciplines such as engineering, soil science, mathematical statistics, even physics, and of course geography, and offering possibilities of intervention especially for the US Army Corp of Engineers. This needs further explanation.

Arthur Strahler did not begin as a Cold War scientist. The Geology programme he entered at Columbia as a graduate student in 1938 (and typical of US Geology Departments) practised what he later called a "pre-paradigm," "qualitative/descriptive geomorphology" (Strahler, 1992, pp. 65–66). It was a pre-paradigm, following Kuhn, because it had not yet become even a science. His PhD dissertation completed in 1944, and written within that pre-paradigm, was, he now says, "largely a waste of time" (Strahler, 1992, p. 67). But less than a year later comes his Pauline experience: reading in March 1945 Horton's (1945) paper. It introduced him to a quantitative approach to geomorphology, leading him to audit courses in statistics across Campus given in economics and biometrics, and to the possibilities of cyborg history. For Horton's paper represented a "remarkable interdisciplinary transfer of information from hydrology ... to geomorphology" (Strahler, 1992, p. 69). Geology's first paradigm was about to begin.

It began as most paradigms do with dispensing of rivals. At the 1950, annual meeting of the Association of American Geographers, Strahler in the opening paragraph to his paper, called William Morris Davis's qualitative/descriptive approach, "superficial and inadequate" (Strahler, 1992, p. 72). Over the next decade, the new paradigm was filled out, called by Strahler (1992, p. 65) "quantitative/dynamic geomorphology." In filling out that paradigm I am not implying Strahler deliberately strove to emulate Cold War science. Clearly, he was frustrated with existing approaches, just as Tobler and Garrison were. He was looking for alternatives, and Horton's paper was the bridge that enabled him to cross over to an already existing Cold War science that met his new intellectual expectations, provided him status, and gave him and students funds for his research. Haraway (1997) has written about "contemporary millenarian technoscience,'' as she calls it, the roots of which she argues are in the Cold War. She borrows the term ''hailing'' from Louis Althusser to understand how people and things become ''interpellated'' within it (Haraway, 1997, pp. 49–51). They don't do so self-consciously in a deliberate act of choice; nevertheless they are irresistibly drawn in. The same holds for Strahler; whether he knew it or not, he was hailed and interpellated by the Cold War.

Like Tobler and Garrison, there were larger consequences. As Richard Chorley put it in reflecting on his move to Columbia as a graduate student in 1951, ''I had stumbled into the control centre of a scholarly revolution'' (quoted in Schumm, 2004, p. 672). It was not only geology that was transformed, but physical geography. When Chorley returned to Cambridge in 1958 he taught with Peter Haggett in the first year laboratory, with David Harvey as demonstrator, and they immediately introduced quantitative analysis, ''to do with statistical methods, matrices, set theory, trend surface analysis, and network analysis'' (Chorley, 1995, 361). Chorley brought back from Cold War America a very different conception of physical geography and set of practices, and along with Haggett over the following decade, he set about spreading the word, and the word became *Models in Geography* (Chorley and Haggett, 1967).

5. Conclusion

In this paper I tried to join the small story of geography's quantitative revolution that affected all aspects of the discipline, and the even smaller stories of particular individual lives, with the much larger one of the Cold War. Such stories do not fit inside one another perfectly like a set of Russian nesting dolls. I think this is the problem that DeLillo addresses in *Underworld*, and which explains his fragmented non-linear narrative, the mixture of real and fictional characters, and stubborn material presences like the baseball Bobby Thompson tomahawks into the bleachers. But the stories are nonetheless connected. Even the baseball's. DeLillo (1997, 825) says, ''There are only connections. Everything is connected ... world without end, amen.''

In my account, what did the connecting was the Cold War. It was there at every turn. It has long been known that the institutional development of geography in Western Europe during the nineteenth century as a discipline was linked with the military, in the service of Empire. My argument has been that the military remained a significant presence even in the mid-twentieth century. Of course, the precise role that the military played was different, but the effect on geography was just as important. During the earlier period of Empire, the military were interested in geography because of the traditional skills that the discipline brought – the drawing and interpreting of maps, the understanding of topographic features, the knowledge of regions and their boundaries. Geographers did what they always did, and while they might have come out of imperial war as changed individuals, the discipline they practised did not significantly alter. But this was not true in the later period. The discipline's very centre was displaced, shifted and realigned, mangled, in part because of its connections to the military, its connections to the Cold War.

This fact has not been usually recognised. It is one of the discipline's secrets. In this sense DeLillo's motif of the underworld is again useful. The underworld is where secrets are kept. But secrets eventually seep out, entering ''the marrowed folds of the bone'' as DeLillo (1997, p. 803) puts it. I wouldn't claim anything so grand for this paper. But geography does have its secrets, does have its underworld, and some of those secrets as I tried to show in this paper have entered the discipline's marrow.

Acknowledgements

I would like to thank the past and present editors of Geoforum for honouring me by their invitation to give the first Geoforum Lecture at the San Francisco annual meeting of the Association of American Geographers, April 2007. The research was funded by a Canada SSHRC grant.

References

Allison, D.K., 1985. U.S. Navy Research and development since World War II. In: Smith, M.R. (Ed.), Military Enterprises and Technological Change: Perspectives in the American Experience. MIT Press, Cambridge, MA, pp. 289–329.

Arib, M.A., Hesse, M.B., 1986. The Construction of Reality. Cambridge University Press, Cambridge.

Barnes, T.J., 2004. Placing ideas: Genius Loci, heterotopia, and geography's quantitative revolution. Progress in Human Geography 29, 565–595.

Barnes, T.J., 2006. Geographical intelligence: American geographers and research and analysis in the Office of Strategic Services, 1941–1945. Journal of Historical Geography 32, 149–168.

Barnes, T.J., Farish, M., 2006. Between regions: science, militarism, and American geography from World War to Cold War. Annals of the Association of American Geographers 96, 807–826.

Bernstein, M., 1995. American economics and the national security state, 1941–53. Radical History Review 63, 8–26.

Boumans, M., 1999. Built-in justification. In: Morgan, M.S., Morrison, M. (Eds.), Models as Mediators: Perspectives on Natural and Social Science. Cambridge University Press, Cambridge, pp. 66–96.

Cartwright, N., 1983. How the Laws of Physics Lie. Clarendon Press, Oxford.

Cartwright, N., 1999. The Dappled World: A Study of the Boundaries of Science. Cambridge University Press, Cambridge.

Chorley, R.J., 1995. Haggett's Cambridge: 1957–66. In: Cliff, A.D., Gould, P.R., Hoare, A.G., Thrift, N.J. (Eds.), Diffusing Geography: Essays for Peter Haggett. Blackwell, Oxford, pp. 355–374.

Chorley, R.J., Haggett, P., 1967. Models in Geography. Edward Arnold, London.

Clarke, K.C., Cloud, J., 2000. On the origins of analytical cartography. Cartography and Geographic Information Science 27, 195–204.

Cloud, J., 2002. American cartographic transformations during the Cold War. Cartography and Geographic Information Science 29, 261–282.

Cloud, J., 2003. Introduction: special guest editorial issue on the earth sciences in the Cold War. Social Studies of Science 33, 629–633.

Cochrane, R.C., 1978. The National Academy of Sciences: The First Hundred Years, 1863–1963. Academy, Washington, DC.
Cohen, I.B., 1988. The computer: a case study of the support by government, especially, the military, of a new science and technology. In: Mendelsohn, E., Smith, M.R., Weingart, P. (Eds.), . In: Science, Technology and the Military: Sociology of the Sciences Yearbook, vol. 12. Kluwer, Dordrecht, pp. 119–154.
Collins, M.J., 2002. Cold War Laboratory: RAND, the Air Force and the American State, 1945–50. Smithsonian Institute Press, Washington, DC.
da Costa, N., French, S., 2000. Models, theories and structures: thirty years on. Philosophy of Science 67S, S116–S127.
Deleuze, G., Parnet, C., 1987. Dialogues. University Press, New York, Columbia.
DeLillo, D., 1997. Underworld. Scribner, New York.
Deutsche, K.W., Platt, K., Senghaas, D., 1971. Conditions favoring major advances in social science. Science 171, 450–459.
Doel, R.E., 2003. Constituting the post war earth sciences: the military's influence on the environmental sciences in the USA after 1945. Social Studies of Science 33, 635–666.
Edwards, P., 1996. The Closed World: Computers and the Politics of Discourse in Cold War America. MIT, Cambridge, MA.
Forman, P., 1989. Behind quantum electronics: national security as basis for physical research in the United States, 1940–60. Historical Studies in the Physical Sciences 18, 149–229.
Fuller, S., 2000. Thomas Kuhn: A Philosophical History for Our Times. University of Chicago Press, Chicago.
Garrison, W.L., 1998. Interview with the Author. Berkeley, CA, March.
Garrison, W.L., 2002. Lessons from the design of life. In: Gould, P., Pitts, F.R. (Eds.), Geographical Voices. Syracuse University Press, Syracuse, NY, pp. 99–123.
Garrison, W.L., Berry, B.J.L., Marble, D.F., Nystuen, J.D., Morrill, R.L., 1959. Studies of Highway Development and Geographic Change. University of Washington Press, Seattle, WA.
Gerovitch, S., 2001. Mathematical machines of the Cold War: Soviet computing, American cybernetics and ideological disputes in the early 1950s. Social Studies of Science 31, 253–287.
Hacking, I., 1983. Representing and Intervening: Introductory Topics in the Philosophy of Natural Sciences. Cambridge University Press, Cambridge.
Haraway, D.J., 1997. Modest_Witness@Second_Millenium.Female. Man© Meets_Oncomouse™. Routledge, London.
Hartshorne, R., 1939. The Nature of Geography: A Critical Survey of Current Thought in the Light of the Past. Association of American Geographers, Lancaster, PA.
Hartshorne, R., 1955. Exceptionalism in geography reexamined. Annals of the Association of American Geographers 45, 205–244.
Harvey, D., 1969. Explanation in Geography. Edward Arnold, London.
Hesse, M., 1966. Models and Analogies in Science. University of Notre Dame, Notre Dame, IN.
Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bulletin Geological Society of America 56, 275–370.
Hounshell, D., 1997. The Cold War, RAND, and the generation of knowledge, 1946–60. Historical Studies in the Physical Sciences 27, 237–267.
Hughes, T.P., 1998. Rescuing Prometheus. Pantheon, New York.
Hughes, A.C., Hughes, T.P. (Eds.), 2000. Systems, Experts, and Computers: The Systems Approach in Management and Engineering, World War II and After. MIT Press, Cambridge, MA.
Jardini, D.R., 2000. Out of the blue yonder: the transfer of system thinking from the Pentagon to the Great Society. In: Hughes, A.C., Hughes, T.P. (Eds.), Systems, Experts, and Computers: The Systems Approach in Management and Engineering, World War II and After. MIT Press, Cambridge, MA, pp. 311–357.
Kay, L.E., 2000. Who Wrote the Book of Life? A History of the Genetic Code. Stanford University Press, Stanford, CA.
Krugman, P., 1995. Development, Geography, and Economic Theory. MIT Press, Cambridge, MA.
Kuhn, T.S., 1962. The Structure of Scientific Revolutions. University of Chicago Press, Chicago.
Latour, B., 1987. Science in Action: How to Follow Scientists and Engineers Around in Society. Harvard University Press, Cambridge, MA.
Leslie, S.W., 1993. The Cold War and American Science: The Military–Industrial–Academic Complex at MIT and Stanford. Columbia University Press, New York.
Lévi-Strauss, C., 1966. The Savage Mind. University of Chicago Press, Chicago (first published in French in 1962).
MacKenzie, D., 2003. An equation and its worlds: bricolage, exemplars, disunity and perfomativity in financial economies. Social Studies of Science 33, 831–868.
McMullin, E., 1968. What do physical models tell us? In: van Rootselaar, B., Staal, J.F. (Eds.), Logic, Methodology and Philosophy of Science III. North Holland, Amsterdam, pp. 385–400.
Mirowski, P., 2002. Machine Dreams: Economics Becomes a Cyborg Science. Cambridge University Press, Cambridge.
Morrill, R.L., 1984. Recollections of the "quantitative revolution's" early years: the University of Washington, 1955–65. In: Billinge, M., Gregory, D., Martin, R.L. (Eds.), Recollections of a Revolution: Geography as Spatial Science. Macmillan, London, pp. 57–72.
Morrison, M.S., Morgan, M., 1999. Models as mediating instruments. In: Morgan, M.S., Morrison, M. (Eds.), Models as Mediators: Perspectives on Natural and Social Science. Cambridge University Press, Cambridge, pp. 10–37.
Pickering, A., 1995a. Cyborg history and the World War II regime. Perspectives on Science 3, 1–47.
Pickering, A., 1995b. Concepts and the mangle of practice: constructing quaterions. South Atlantic Quarterly 94, 417–465.
Pickering, A., 1995c. The Mangle of Practice: Time, Agency and Science. University of Chicago Press, Chicago.
Pickering, A., 1995d. Explanation, agency, and metaphysics: a reply to Owen Flanagan. South Atlantic Quarterly 94, 475–480.
Schaefer, F.K., 1953. Exceptionalism in geography: a methodological introduction. Annals of the Association of American Geographers 43, 226–249.
Schorske, C.E., 1997. The new rigorism in the human sciences, 1940–60. Daedalus 126, 289–309.
Schumm, S.A., 2004. In memoriam: Arthur Newell Strahler (1918–2002). Annals of the Association of American Geographers 94, 671–673.
Strahler, A.N., 1992. Quantitative/dynamic geomorphology at Columbia 1945–60: a retrospective. Progress in Physical Geography 16, 65–84.
Suppes, P., 1961. A comparison and meaning of models in the mathematical and empirical sciences. In: Freudenthal, H. (Ed.), The Concept and the Role of the Model in Mathematics and Natural and Social Sciences. Reidel, Dordrecht, pp. 163–177.
Tobler, W., 1959. Automation and cartography. The Geographical Review 49, 526–534.
Tobler, W., 1976. Analytical cartography. The American Cartographer 3, 21–31.
Tobler, W., 2000. The development of analytical cartography: a personal note. Cartography and Geographic Information Science 27, 189–194.
Tobler, W., 2002. Ma vie. In: Gould, P., Pitts, F.R. (Eds.), Geographical Voices. Syracuse University Press, Syracuse, NY, pp. 293–322.
van der Bogaard, A., 1999. Past measurement and future prediction. In: Morgan, M.S., Morrison, M. (Eds.), Models as Mediators: Perspectives on Natural and Social Science. Cambridge University Press, Cambridge, pp. 282–325.
Wiener, N., 1961 [1948]. Cybernetics: Or the Control and Communication in the Animal and the Machine, 2nd ed. MIT Press, Cambridge, MA.