Physical Methods in the Twentieth Century Between Disciplines and Cultures

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Introduction

This paper aims at contributing to the history of a type of science that focuses on the development and dissemination of research methods.[1] Although, as I will argue, the 'making of methods' is a crucial and widespread activity in twentieth-century science, it is not well represented in its historiography.[2] Similarly to research technologists,[3] 'method makers' are invisible because they represent hybrid, or interstitial, careers, respectively activities. Moreover, we may be blinded by one of the myths of science, according to which it is the solution of problems that counts as the true, and sometimes only, activity of scientists. The development of methods is, thus, just an intermediate step in the process of scientific research. By and large, these intermediate steps are forgotten, or suppressed, in both scientific and historiographical accounts.

In mid-twentieth century, I will argue, a novel socio-epistemic field of scientists focusing on the development of research methods came into existence, connecting instrument manufacturers, academic disciplines and professions, and governmental science funding agencies. Three relationships are best suited to characterize the socio-epistemic field of the 'method makers.' First, their relations inside academic disciplines and research fields. The basis for this is the research practice, most notably the influence of high-tech instrumentation on experiments and data management. Second, the academic-industrial partnership, most importantly that of academic scientists with industrial instrument manufacturers. Third, the impact of science funding, and the special relations of method makers with the relevant agencies. In historiographical and sociological research, these three layers, or strands, are largely disconnected. For the first, it is the new experimentalism and laboratory studies; for the second studies of the so-called science-based industry; for the third work about policy and governance. Some notions, such as triple helix, mode 2 and technoscience, are designed to connect these layers. The historian and sociologist of science, Terry Shinn, attempts to connect them as well with his notion of a transversal regime. According to Shinn, recent science is characterized by a plurality of contexts of applications, connected through the transfer of research technologies.[4] However, the ways how research technologies are transferred are in need of further elucidation. Thus, my paper will aim to identify and to characterize a socio-epistemic structure that allows us to better understand these transfers and their working modes.

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[1] This paper is based on Carsten Reinhardt, "Forschungstechnologien im 20. Jahrhundert. Transfer und Transformationen," in: Klaus Hentschel, ed., *Zur Geschichte von Forschungstechnologien. Generizität – Interstitialität – Transfer*, Diepholz: GNT-Verlag 2012, pp. 277-307.

[2] But see Patricia Nevers, Raimund Hasse, Rainer Hohlfeld, Walther Zimmerli, "Mediating Between Plant Science and Plant Breeding: The Role of Research Technology," in: Bernward Joerges, Terry Shinn, eds., *Instrumentation Between Science, State and Industry*, Dordrecht: Kluwer Academic Publishers 2001, pp. 97-118.

[3] Terry Shinn, "The Triple Helix and New Production of Knowledge: Prepackaged Thinking on Science and Technology," *Social Studies of Science* 32/4 (2002), 599-614.

[4] Terry Shinn, "New Sources of Radical Innovation. Research Technologies, Transversality, and Distributed Learning in a Post-industrial Order," in Jerald Hage, Marius Meeus, eds., *Innovation, Science, and Institutional Change*, Oxford: Oxford University Press 2006, pp. 313-333; Terry Shinn, Pascal Ragouet, *Controverses sur la science. Pour une sociologie transversaliste de l'activité scientifique*, Paris 2005.

Still today, the development of methods is marginalized in science. An example is the editorial of a new journal, *Nature Methods*, in 2004. Titled "Methods for Methods' Sake", the editorial laments the neglect of the coverage of methods development in 'regular' journals.[5] However, and in stark contrast to this neglect, the impact of methods development on science is huge: 'method makers' work with and on all kinds of research instrumentation, ranging from big science to table-top instruments. They interact with a multitude of groups of scientists (their 'clientele') in different disciplines, and they have close cooperations with industrial instrument manufacturers. Many of their activities rest on the standardization and commercialization of research instrumentation that can be used by large groups of scientists in academia, government, and industry.

To scrutinize the field of method makers, I use Pierre Bourdieu's concepts of habitus and field.[6] Each (scientific) field generates social structures, and these are governed by the distribution of symbolic capital. The command over research methods, and the ruling over their accurate and justified use, is one of the possibilities for scientific actors to change the rules of the game for the acquisition of symbolic capital. (There are others, of course, as well.) Thus, method makers have a unique access to power in a scientific field, and can be easily regarded as subversive by the establishment.[7] Access to research methods can lead directly to scientific reputation. With regard to Bourdieu's phrase that the clients of scientists are their competitors as well (because the use of scientific knowledge is in the further development of it), we note an interesting exception: method makers are only indirectly the competitors of their clients, because they work for the use and dissemination of their methods and they intrude into problem solving only insofar as this is needed to prove the usefulness and impact of the method in question. The users (clients), moreover, have an interest in receiving ready-to-use, routine research methods and welcome an occasional intrusion with regard to high-end problem solving. This may be regarded as a win-win situation. In consequence, we will need to ask if the method makers generate their own scientific-technical field, and to what extent they are able to establish their autonomy with regard to their users. Moreover, we may ask if this represents an 'internal periphery,' as the constitutive industrial and governmental relations, which are normally seen as exogenous, now play an endogenous role, as they are included in the field.

1. Methods of isolation, identification, and interpretation

In order to establish my case, I wish to address a conglomerate of research technologies that increasingly gained momentum in the twentieth century. Many mid-size instruments used in physics, biology, chemistry, medicine and engineering can be differentiated into methods of isolation, identification, and interpretation. The first class, or family, of instruments serves the separation and purification of materials. Noteworthy are the chromatographic techniques, but also electrophoresis and the ultracentrifuge. Next come the detecting techniques, most notably the spectroscopies. Of course, isolation normally entails identification, and spectroscopy works without isolation in many cases. But often these two classes are not competing, but coupled and work in tandem. The third class is that of interpretation, and I refer to the

[5] "Methods for Methods' Sake," Editorial, *Nature Methods* 1 (2004), 1.

[6] Pierre Bourdieu, *Vom Gebrauch der Wissenschaft. Für eine klinische Soziologie des wissenschaftlichen Feldes*, Konstanz: UVK Universitätsverlag 1998; Carsten Reinhardt: "Habitus, Hierarchien und Methoden. 'Feine Unterschiede' zwischen Physik und Chemie," *N.T.M.* 19 (2011), 125-146.

[7] Carsten Reinhardt, "Zentrale einer Wissenschaft. Methoden, Hierarchie und die Organisation der chemischen Institute," in Rüdiger vom Bruch, Heinz-Elmar Tenorth, eds., *Geschichte der Universität Unter den Linden 1810-2010. Biographie einer Institution, Praxis ihrer Disziplinen*, volume 5, *Transformation der Wissensordnung. Verwissenschaftlichung der Gesellschaft und Verstaatlichung der Wissenschaft*, Berlin: Akademie Verlag 2010, pp. 575-603.

computer, and algorithms. Most visibly this is the case with the applications of artificial intelligence,[8] but there are many more cases. Access to all of these functions is of crucial importance for any researcher, and often these methods establish a large part of the identity in a discipline.[9] On the epistemic level, changes in the three classes, or families, of research methods contributed to the expansion, and partial transformation, of structural thinking in the relevant scientific disciplines during the twentieth century. The 'mental model' of thinking in molecular structures [10] expanded into biology, physics, and later into nanotechnology, materials science and others. Alongside with this epistemic development, the emergence of a new type of scientist, that of a method-based expert, or specialist, can be traced. The following model of method-based expertise will explain, to a certain extent, how method makers could connect academic science, industrial manufacturing, and governmental policy.

2. Method-based expertise

'Normally,' scientists search for methods that can be used to solve problems, which are in turn established by theories or applications. Method makers, in contrast, search for problems that are ready to be solved with their newest method at hand. My hypothesis, in a nutshell, is that in mid-twentieth century a division of labor between these two intertwined parts of scientific practice took place. Specialists for the development and use of instruments, and the related development of suitable methods complemented problem-solving researchers. I have analyzed their relation with the model of expertise,[11] and would like to add here that Bourdieu's field model enables us to understand the possibilities for respective gains in symbolic capital, for both sides at the same time.

It would be expected that the introduction of a whole new set of experimental methods for isolation, identification and interpretation into so many disciplines and sub-disciplines would have resulted in an overthrowing of traditional hierarchies inside disciplines. However, the novel methods did not completely change the power structures in the scientific field, though they crucially influenced its course and structure, and they institutionalized new relationships between scientists. An often-used term for the relevant interactions is scientific cooperation,[12] and we see here that in the 1960s, the cooperation between method makers and their clients was institutionalized. An important case is that of the *facilities* or *special research resources* of the U.S. National Institutes of Health (NIH).[13] In 1977, 52 centers were in use in the U.S., with a range from computers to spectroscopies and imaging technologies. NIH introduced the categories of service, training, cooperation, and core research to characterize the functions of the centers. This enabled the scientists in charge of these special research resources (almost always placed at major research universities) to establish their specialty while at the same time influencing, and catering for, a scientific field. At the same time, most chemistry departments at universities expanded their analytical laboratories into

[8] Carsten Reinhardt, *Shifting and Rearranging. Physical Methods and the Transformation of Modern Chemistry*, Sagamore Beach, Mass.: Science History Publications 2006, chapter 5.

[9] Mary-Jo Nye, *From Chemical Philosophy to Theoretical Chemistry. Dynamics of Matter and Dynamics of Disciplines, 1800-1950*, Berkeley: University of California Press 1994.

[10] Thomas Steinhauser, *Zukunftsmaschinen in der Chemie. Kernmagnetische Resonanz bis 1980*, Frankfurt am Main: Lang Verlag 2012.

[11] Carsten Reinhardt, "Expertise in Methods, Methods of Expertise," in Martin Carrier, Alfred Nordmann, eds., *Science in the Context of Application* (Boston Studies in the Philosophy of Science 274), Dordrecht: Springer 2011, pp. 143-159.

[12] Jane Maienschein, "Why Collaborate?" *Journal of the History of Biology* 26 (1993), 167-183; Ivan Chompalov, Joel Genuth, Wesley Shrum, "The Organization of Scientific Collaborations," *Research Policy* 31 (2002), 749–767.

[13] Carsten Reinhardt, "Wissenstransfer durch Zentrenbildung. Physikalische Methoden in der Chemie und den Biowissenschaften," *Berichte zur Wissenschaftsgeschichte* 29 (2006), 224-242.

service laboratories in charge of acquiring, maintaining, and developing an ever-growing array of instruments and techniques.[14]

For saving resources, instruments were often shared, and this cost-saving argument played a large role in the establishment, and maintenance, of regional and national centers. At the same time, however, some of the new methods were performing so well, and so efficiently, that their capacity exceeded the abilities of a single small research group to come up with interesting problems. Thus, the (technical) performance in data acquisition and interpretation contributed to driving the establishment of centers, and it led to more and more collaborative (research) projects. At the same time, the sharing of the instrument was closely connected to teaching, and training.

For all concerned, centers of various sizes constituted a win-win situation. Method makers (scientists) gained access to relevant communities of users/clients in scientific disciplines. Instrument manufacturers generated a market for their instruments. Science funding agencies could point to driving scientific progress while at the same time having economic impact and acting with cost-efficiency in mind. For the clientele of scientists in academia and industry, this arrangement constituted the right distance to the development of novel methods. Interestingly, we can observe an analogous development in medicine at the same time. As Stuart Blume has analyzed, radiologists formed a similar community standing between the clinic and the medical device manufacturers. In this case, the different size of the industry (multinationals), and the different economics involved led Blume to coin the phrase of the *medical-industrial complex*.[15] In both cases, the question of governing modes requires attention.

3. Research or innovation? The regulation of research methods

In January 1957, members of the *Divisional Committee of Mathematical, Physical and Engineering Sciences* of the National Science Foundation (NSF) opined that the new research technologies challenged the established means of science funding:

"Effective as it is, the research grants program is able to supply only the most modest of the scientists' needs for research equipment. Much can still be done with test tubes, slide rule, paper and pencil, but there is now convincing evidence that great scientific discoveries are to be expected through the development and use of the expensive new tools of scientific research. The necessary funds to provide such equipment are not now available."[16]

But money alone wasn't the problem. The question was the distribution of funds. The tools of big science, such as particle accelerators, research ships and observatories, required special programs, just because of their sheer size and cost. "Research apparatus for infrared, ultraviolet, Raman, mass, and nuclear magnetic resonance spectra and for many other uses," however, was a category that normally had been integrated into research projects and their funding. To find a solution of this bottleneck was an urgent task: "Practically all areas of the

[14] Pierre Laszlo, "Tools, Instruments and Concepts. The Influence of the Second Chemical Revolution," in Peter J. T. Morris, ed., *From Classical to Modern Chemistry*, Cambridge: Royal Society of Chemistry 2002, pp. 171-187.

[15] Stuart S. Blume, *Insight and Industry. On the Dynamics of Technological Change in Medicine*, Cambridge, Mass.: MIT Press 1992; Carsten Timmermann, Julie Anderson, eds., *Devices and Designs. Medical Technologies in Historical Perspective*, Houndmills: Palgrave Macmillan 2006; Stefan Timmermans, Marc Berg, "The Practice of Medical Technology," *Sociology of Health and Illness* 25 (2003), 97-114.

[16] National Science Foundation (NSF), MPE Divisional Committee, Chairman Thomas K. Sherwood to Bronk and Waterman, 21 January 1957. National Archives Record Administration (NARA), RG 307, Office of the Director, General Records, 1949-63, 1960-61, Box 48, folder Division of M, P, and ES.

physical and biological sciences are characterized today by an accelerating development of instrumental techniques permitting types of measurements and precisions which were not known a few decades ago. (...) As the pace of scientific advancement quickens, the amount and quality of research that is performed in some areas is limited by the sheer expense of such instruments."[17]

For chemistry, NSF in 1957 established a program to specifically support "research instruments."[18] In the 1960s, it had a percentage of between 5 and 20% of all chemistry-related research projects funded by the National Science Foundation.[19] But the difference between research and equipment was never solved completely, and academic chemists had to lobby for the special role that instruments now played for their daily laboratory routine.[20] The situation was similar in the bio-medical field, when scientists claimed the establishment of instrument centers and the introduction of a "biological engineer" degree. Paul E. Klopsteg, a staff member of the National Science Foundation, in the so-called Klopsteg-Report of 1956 called for a union of physics and biology, already in education.[21] In a similar way argued members of the Biophysics and Biophysical Chemistry Study Section of the National Institutes of Health (NIH), founded in 1955. The early roots of the above-mentioned special research resources can be traced back to this period. However, until the mid 1960s the rich supply with funding through governmental agencies allowed a smoothing over the structural deficits. The economic crisis of the late 1960s then led to a cutting-back especially with regard to equipment. For example, the proportion of instruments budgets in the total funding amount of NSF and NIH decreased from 12% to 6% between 1966 and 1971.[22]

This crisis of the late 1960s threatened the supremacy of science, American style. The physicist Philip H. Abelson, president of the Carnegie Institution and editor of *Science*, wrote in 1971:

"To a large extent, American leadership in science has been based on the widespread availability of excellent instrumentation. (...) Current trends indicate that, in the future, leadership in science will be even more contingent on pioneering the use of new and increasingly powerful equipment. American scientists are fortunate in having the support of an innovative instrumentation industry that has been a by-product of federal support of research. The grants system placed considerable sums of money at the disposal of a large number of investigators who were a good market for effective apparatus."[23]

The biochemist Philip Handler, president of the National Academy of Sciences, was of the same opinion:

"Similarly, the commercial development of the electrostatic accelerator, the mass

[17] *Federal Financial Support of Physical Facilities and Major Equipment for the Conduct of Scientific Research. A Report to the Bureau of Budget*, Washington D.C: National Science Foundation, June 1957, p. 42.

[18] Jeffrey K. Stine, "Scientific Instrumentation as an Element of US Science Policy: National Science Foundation Support of Chemistry Instrumentation," in Robert Bud, Susan E. Cozzens, eds., *Invisible Connections. Instruments, Institutions, and Science*, Bellingham: SPIE Optical Engineering Press 1992, pp. 238-263, here pp. 241-242.

[19] Stine (note 18) and Appendix A of Roberts to Haworth, 13. August 1963, NARA, RG 307, NSF Office of the Director subject Files, MPS Chemistry folder, 307-75-051, box 3; NSF annual reports 1965, 66, 67, 72, 73.

[20] Stine (note 18).

[21] National Research Council, Biology Council, *Instrumentation in Bio-medical Research. Report of a Survey by Paul E. Klopsteg*, Washington D.C., 1956 (National Academy of Sciences, National Research Council Publication 472).

[22] Jeffrey K. Stine, Gregory A. Good, "Government Funding of Scientific Instrumentation. A Review of U.S. Policy Debates Since World War II," *Science, Technology and Human Values* 11 (1986), 34-46, here p. 42.

[23] Philip H. Abelson, "The Role of Scientific Instrumentation," *Science* 174 (1971), no. 4014, Editorial.

spectrometer, the nuclear-resonance spectrometer, the electron microscope, high-pressure equipment, and hundreds of other instruments, initially handmade with great travail by laboratory scientists, has permitted researchers to concentrate on the scientific questions rather than on merely reproducing research technologies already pioneered by others. The rapid commercialization of laboratory techniques and instruments has generated a new style of research in which the United States has been in the lead. It has been made possible by the quality and scale of United States research activity, the magnitude of Federal development programs, and the entrepreneurship of our industry."[24]

Here we recognize the triad of the involved institutions: Governmental science funding led to a boom in the instruments manufacturing industry, and on this the success of the scientists depended.[25] We can find this intertwinement also at the level of specific research technologies. In 1980, C.V. Shank of Bell Laboratories, one of the inventors of a dye laser applied in high-speed spectroscopy, wrote:

"It is apparent that with the freedom to develop a new dye laser instrument capable of generating very short pulses, we have been able to influence a broad range of scientific endeavors. (...) Many of the techniques which we have developed have become or are becoming commercial products. The field of the investigation of picosecond phenomena was one that began in the early 60s with a great deal of excitement and enthusiasm but interest began to wane because of the difficulty in making measurements with primitive equipment. We now see this area of picosecond phenomena beginning to show a great deal of growth with the availability of commercial equipment."[26]

Thus, method makers construed their own scientific-technical fields, using the commercial impact of their instruments. In a sense, method-makers relied two-fold on governmental research funding: First, they needed funds to develop their methods, and the related instruments. Second, they depended on the availability of resources for their scientists-clients to buy the necessary instrumentation. These resources had a substantial size. In 1982, the number of instruments at US universities in the range of 10,000 $ to 1,000,000 $ per piece was estimated to be 25,000 in the physical sciences, the computer sciences and engineering—totaling one billion US$. Chemistry had a share of 25 %, physics (without big science) 22%, engineering 33%. Approx. 50% of the instruments were older than five years, 30% older than 10. 57% of cost was paid by federal agencies, with the National Science Foundation and the Department of Defense being the biggest spenders.[27]

Since the mid 1970s, when it became clear that budget cuts would lead to an erosion of US research capabilities, scientists and members of governmental agencies attempted to stem the tide. At a meeting in March 1976, scientists asked the National Academy of Sciences

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[24] Philip Handler, *The Physical Sciences. Report of the National Science Board Submitted to the Congress*, Washington D.C.: Government Printing Office 1970, p. 24.

[25] Carsten Reinhardt, Thomas Steinhauser, "Formierung einer wissenschaftlich-technischen Gemeinschaft. NMR-Spektroskopie in der Bundesrepublik Deutschland," *N.T.M.* 16 (2008), 73-101; Steinhauser (note 10).

[26] Charles V. Shank, "The History of Subpicosecond Optical Spectroscopy," in Association of American Universities, *The Scientific Instrumentation Needs of Research Universities. A Report to the National Science Foundation*, Washington D.C., June 1980, Appendix 1, pp. 30-31, here p. 31.

[27] Kenneth Burgdorf, Kristine White, *Academic Research Equipment in the Physical and Computer Sciences and Engineering. An Analysis of Findings from Phase I of the National Survey of Academic Research Instruments and Instrumentation Needs*, Rockville: Westat Research Inc. 1984, pp. 20, 23, 28.

to lead a study addressing “the general problem of major instrumentation for chemistry and biology”[28] and in July 1976 two of the involved scientists summarized the sitiation as follows:

“One of the most important problems facing research in chemistry and biology today is the escalating sophistication, size, and associated costs of major instrumentation. (...) The performance level of these instruments is often orders of magnitude ahead of their previous state-of-the-art counterparts, and they offer unusual opportunities for major breakthroughs in many areas of research. Effective usage of some of this sophisticated instrumentation, and efficient use of instrumentation dollars may require new institutional mechanisms (i.e. cooperative efforts and facilities) for research.”[29]

The speed of innovation of instrumentation, to a large degree accelerated by the very same scientists involved in the study, led to an increase in spending needs. But rarely the situation was described as bluntly as by a representative of the department of energy in 1982: “The instrumentation problem is somewhat like the balance between food supply and population in primitive societies. If a tribal group, living at the margin of survivabilty, discovers a means by which it can increase its food supply, then it begins to overpopulate and gradually finds itself once again living at the margin.”[30]

The scientists argued that the leading international ranking of US science was based to a large extent on previous investments in instrumentation.[31] The pleas based on this argument were twofold: “The first is that funds and opportunities have to be provided for the invention and development of new instruments. (...) The second point is that state of the art instrumentation has to be made accessible to research scientists who need to use it. And, considering the state of tight funding, this requires that instrumentation be shared.”[32] Thus, for two reasons, instrument-sharing became the miracle cure for the problems of the 1970s and early 1980s: Fewer means, and an improved channeling of access worked hand in hand, and the latter worked for the benefit of the method makers.[33] In 1984, a third of the instruments in the Physical Sciences were shared, in computer science 82%.[34]

Thus, it became clear to those involved that access to instrumentation, and especially the capability of instrument and methods innovation, constituted an instrument of science policy. In 1981, the Biotechnology Resource Program of NIH held two workshops on the technical support of the life sciences. The 65 delegates from science, industry and government postulated a linear model of problem solving, which showed a convergence of the identification of problems and the development of new technologies leading to the distribution of methods and their availability. For the panel, the problematic issue was the lack in the development of risky technologies, caused by the shortfall of physicists and

[28] John D. Roberts et al. to Philip Handler, 15 March 1976, Oleg Jardetzky Papers, Ad hoc Committee, folder “Notes.”
[29] John D. Roberts, Richard N. Zare, Appendix 3, 1. July 1976, “Report on Ad hoc Panel on Cooperative Efforts and Facilities for Research in Chemistry and Biological Chemistry,” 23 October 1976, National Academy of Sciences. Oleg Jardetzky Papers, Ad hoc Committee, folder “Notes.”
[30] Alvin Trivelpiece, in National Research Council, Office for Physical Sciences, *Revitalizing Laboratory Instrumentation. The Report of a Workshop of the Ad hoc Working Group on Scientific Instrumentation, March 12-13, 1982*, Washington D.C.: National Academy Press, 1982, 17-19, here p. 17.
[31] Elkan R. Blout, D.M. Grant, O. Jardetzky, W.D. Phillips, K.R. Porter, “Instrumentation Funding,” *Science* 202 (1978), no. 4366, Editorial.
[32] Statement Oleg Jardetzky, Subcomittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives, protocol, p. 403, 26. February 1979. Oleg Jardetzky Papers, folder “Ad hoc Committee, Congressional Testimony.”
[33] Charles C. Coulter, “Research Instrument Sharing,” *Science* 201 (1978), 415-420.
[34] Burgdorf, White (note 27), p. 36, fig.15.

engineers in commissions, and especially the lack of recognition of instrument and methods development as being part of science. Thus, they proposed "the interpretation of 'research' be classified and made explicit to include technologic innovation and discovery."[35] The duration and size of projects should be flexible, and the production of prototypes should be included. At the same time, the interaction of universities and industry should be strengthened.

The actors had a much larger market in mind than just universities and governmental research institutions. By far the largest share was held by industry, in both research and manufacturing.[36] Often, the development of novel instrumentation was driven by companies, especially in the petrochemical industry, and this gave rise to important spin offs of instrument manufacturing companies.[37] The global market (the largest 22 nations, with the exclusion of the USA) in 1971 had a size of approx. 3.7 billion US$.[38] For Germany alone the size was estimated to be more than one billion, with a prognosis of 1.5 billion in 1975.[39]

Medical technology had an even larger size: "The industry that manufactures medical devices in the United States has grown (...) from less than $1 billion in 1958 (...) to more than $17 billion in 1983. Even after adjustment for inflation, industry sales increased sixfold during that period."[40] Here, as well, similar mechanisms of research funding and regulation of innovation were in place as a report of the Office of Technology Assessment from 1984 demonstrates:

"A recent analysis of NIH, NSF, and Department of Energy grants and contracts active as of May 1983 revealed that almost $50 million was related to diagnostic imaging. This medical imaging R&D was scattered throughout the institutes and agencies and covered a wide assortment of subjects including not only development or refinement of new imaging devices, but the use of imaging techniques to enhance understanding of disease processes. A high proportion of these grants went to academic and other nonprofit institutions, and therefore supplemented the R&D on medical imaging conducted by industry. NIH funding in the medical imaging area has, in retrospect, had important impacts on the later development of commercial imaging devices."[41]

Thus, innovation of both scientific and medical instruments showed a similar pattern. Funded by governmental agencies, the instrument industry supplied science with the necessary tools. At the same time, method makers enjoyed a key position as they were in charge for growing the market size. However, this led to problems in the funding of universities, as they could not keep pace with the speed of innovation.

Eric von Hippel's model of 'user-dominated innovation' describes the academic partners of instrument manufacturers as users.[42] However, these users were not passive, but actively engaged and stood in a symbiotic relationship with industry. Out of self-interest,

[35] Richard J. Johns, Ernest D. Cravalho, "Final Draft. Workshops on Technology in Support of Biomedical Research," 5. November 1981, p. 5. Oleg Jardetzky Papers, folder "Workshops on Technology in Support of Biomedical Research."

[36] Frost & Sullivan, Inc., *The Analytical Instruments Market*, New York 1972.

[37] Davis Baird, "Encapsulating Knowledge: The Direct Reading Spectrometer," *Foundations of Chemistry* 2 (2000), 5-46; Yakov M. Rabkin, "Technological Innovation in Science. The Adoption of Infrared Spectroscopy by Chemists," *Isis* 78 (1987), 31-54.

[38] U.S. Department of Commerce, *Global Market Survey. Industrial and Scientific Instruments*, Washington D.C.: U.S. Government Printing Office 1972.

[39] U.S. Department of Commerce (note 38) p. 7.

[40] Office of Technology Assessment, *Federal Policies and the Medical Device Industry*, Washington, D. C.: U.S. Congress, Office of Technology Assessment, October 1984 (OTA-H-230), p. 3.

[41] Office of Technology Assessment (note 40), p. 80.

[42] Eric von Hippel, *The Sources of Innovation*, New York: Oxford University Press 1995.

method makers relied on innovation of instruments, in order to grow their scientific capital in form of reputation. The scale and scope of such relationships has been described with the example of a symbiotic competition between the industrial scientist James Shoolery and the academic scientist John D. Roberts, featuring the example of NMR methods and physical organic chemistry.[43] In the biomedical field, Rosenberg, Gelijns and Dawkins emphasize the importance of the cooperation between the industrial instrument manufacturers (with their expertise in electrical engineering) and the clinicians (thus, not the researchers). In this case, the users are a crucial part of innovation, at least in the stage of (clinical) development. At the same time, the authors distinguish the role of NIH in the field of medical technology from such techniques that involve chemical, biological and medical know-how, especially in the pharmaceutical field.[44]

The US style of scientific research, as diagnosed by Abelson and Handler, relied in large parts on the commercial development of research instruments. This was the basis for the method makers' strategy to distribute their methods as widely as possible. At the same time, it changed the definition of research projects in such a way that it included the innovation of instrumentation and the development of methods. The use of instruments outside the academy, for example in industrial and environmental applications, had some beneficial effects, because it decreased the dependance on one sphere of application only. On the other hand, science depended on the commercialization of its main research tools.

4. Methods of Research—a Conclusion

The transformation of research technologies in the middle of the twentieth century was the cradle for a novel type of scientist, with the major goal of development and dissemination of research methods. The support came from governmental science funding agencies and a well performing instrument industry. In the resulting triangle of science, industry and government, method makers had a central, but also precarious, role. Central for their long-term survival was their standing inside the scientific field, as with access to novel methods scientists obtained the means to gain reputation. However, method makers had the potential to threaten established power positions in a discipline. In the end, a middle path was taken, that led to the containment of the new methods in centers, but ensured change and innovation. As a result of this centralization and institutional separation, the transfer of methods through service, training, and cooperation channeled the further development of methods. As experts, the method makers could forward their research, but not completely rule disciplinary trends. The more new methods became routine in certain disciplines, the more urgent it became for method makers to expand their reach. Innovation processes and expert roles of method makers were thus dynamically intertwined. The autonomy of method makers was rooted in their ability to cater for many different clientele groups. Their alliances with instrument manufacturers and funding agencies stabilized their strong standing further. Because many methods were used not just in science but also in industry and government, the circle of science-industry-government relations closed.

Largely originating in World War II, this advantageous constellation developed further in the immediate postwar period. The focus on mid-size and table-top instruments of isolation, identification, and interpretation allows us to trace the transformations in the 1950s and 1960s. The chromatographical and spectroscopical methods, including the data management by computers, entered into the centers of practice of almost all established research directions, and they were constitutive for novel directions as well.

[43] Carsten Reinhardt, "A Lead User of Instruments in Science. John D. Roberts and the Adaptation of Nuclear Magnetic Resonance to Organic Chemistry, 1955-1975," *Isis* 97 (2006), 205-236.

[44] Nathan Rosenberg, Annetine C. Gelijns, Holly Dawkins, *Sources of Medical Technology. Universities and Industry*, Washington D.C.: National Academy Press 1995.