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The Whitesides Lab

> *The main purpose of our research lab is to produce ideas that change the way people think about science.*
> — Professor George Whitesides

Early in his tenure as President of Harvard University, Dr. Lawrence Summers signaled his view that science should play a bigger role in the mission of the University and across society. Harvard's rich tradition and scientific excellence within its Faculty of Arts and Sciences (FAS), Medical School, and associated teaching hospitals offered a model for success. However, tradition, size, and organizational complexity created barriers to the development of new models for advancing science and translating it to benefit society. With recently acquired space in the Allston area of Boston and new access to substantial financial resources, the university had the opportunity to influence the way academic science and its commercialization would be done in the future.

In the fall of 2003, President Summers convened a task force on science and technology to identify needs and opportunities in scientific research at Harvard. Such an assessment would ensure that in a rapidly changing world, Harvard would continue to engage in the most promising areas of science and engineering. It also would provide advice on the allocation of resources—physical and financial—and how to organize scientific activities geographically, given the new opportunities in Allston. The potential was extraordinary because the area was underdeveloped and unprogrammed. The task force recommended that a group of initiatives be clustered in Allston within two complexes of approximately 500,000 square feet each. All the initiatives, which were seen to exemplify the kind of interdisciplinary activity that new ways to collaborate would benefit, could be divided into two groups of initiatives. The first included chemical biology, innovative computing, stem cells, and systems biology; the second included global neglected diseases, microbial sciences, and the origins of life. All these potential activities involved faculty and research staff in the fields of science, engineering, and medicine.

The organization and structure of any one initiative was not yet clear. The research problems of each initiative were multidimensional and required many disciplines and investigators currently scattered in labs on the Harvard campus in Cambridge and medical facilities and hospitals in Boston. By the summer of 2005, many questions still faced Summers and those chosen to lead these new scientific enterprises. For example, what characterized truly creative labs? How could research collaboration across disciplines best be conducted? How should the impact of academic research labs be measured? Could traditional models of highly successful academic labs be scaled up to large, mission-oriented centers?

To understand these issues, the Task Force reflected on the experience of particularly successful labs, such as that of Professor George Whitesides of the Faculty of Arts and Sciences. The Whitesides

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Professor H. Kent Bowen and Lecturer/Postdoctoral Fellow Francesca Gino prepared this case. The authors are grateful to James Weber and Irina Tarsis, both of the Global Research Group, for their assistance.

Lab was large by academic standards (40–50 researchers) and produced groundbreaking research in chemistry and chemical biology, outstanding graduates, and original ideas that led to commercial ventures.

The Whitesides Lab

An ideal project for our group is something in which we start with a question that's fundamental science. We try to understand it, and find out how to apply it. We then build a prototype, and finally do research engineering. And 10 years later there's probably a start-up.

—Professor George Whitesides

George Whitesides was internationally acclaimed as a physical organic chemist at MIT when he returned to his alma mater in 1982 (see **Exhibits 1** and **2** for Whitesides' bio and lab research themes). He joined Harvard's Chemistry Department and was given office and laboratory space on the second floor of an ancient but well-kept building two minutes from Harvard Yard. The facilities were characterized by an open architecture. The lab was over 6,000 square feet, with enough room for 34 workbenches and tables. Scattered among the lab benches and specialized analytical equipment were the researchers' "offices," each of which consisted of a small desk, a file cabinet, and usually one or more whiteboards close by. Along the hall, rooms with computer workstations alternated with laboratories where each researcher had his or her work area. Walls were covered both with posters displaying results of current projects or with whiteboards on which lab members tracked their ideas, notes, and calculations (see **Exhibit 3** for photos).

The lab retained the strong culture of scientific rigor imprinted by Whitesides, requiring researchers to draw deeply from disciplinary knowledge, yet also strongly encouraged collaborative work that integrated knowledge and experimental techniques far from chemistry. New members to the lab were warned that while it appeared that Whitesides had a "hands-off approach," he nevertheless reviewed the status of each project regularly. Katie Drake Gudiksen, a graduate student who had been working in Whitesides' lab for three years, explained,

> Before joining George's lab in 2002, I worked in another lab. If I think about it, there were three differences between the two labs. First, George has a hands-off approach. In the other lab, the leader was the source of ideas and the work was driven by his authority. Second, research [in the Whitesides Lab] is much more collaborative. Third, the research is multidisciplinary. Researchers within their [project] group and in their interaction with George have the opportunity to look at a problem from different perspectives.

Individual initiative and long working hours were the norm. The lab included over 40 members (see **Exhibits 4** and **5**). On average, about half were doctoral students and half were postdocs.[1] The lab had produced over 300 graduates (PhDs, postdocs, and visiting scientists). Postdocs stayed one to three years, while doctoral students required four to six years to complete their coursework and thesis research. A lab administrator, two secretaries, and two assistants completed the lab staff. In addition, during the summer, six Harvard undergraduates worked at the lab, with two or three of them continuing during the school year. Researchers had very different backgrounds and research interests. As Whitesides described the mix,

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[1] The postdoctoral annual stipend was set by National Institutes of Health (NIH) guidelines and ranged between $35,500 and $41,700 from the first to third year of an appointment. Graduate students' stipends averaged $26,000/year, some of which went to tuition.

> The business of the lab is doing first experiments. And that requires a big group with a lot of skills, [and] imaginative people. The graduate students are mostly chemists and materials scientists, with a few biologists. The postdoctoral students are everything - they're electrical engineers, chemical engineers, physicists, biologists, and [MDs].[2]

The process for selecting graduate students differed from that for selecting postdocs. Graduate students were selected by a departmental committee in which Whitesides did not belong. They were selected on such criteria as how well they had done in courses and whether they had done undergraduate research. Graduate students were admitted without any particular interest in a professor's research; they may or may not have expressed preferences. As Whitesides described the selection process,

> The characteristic of our lab is that you don't find what we do as something which is taught in undergraduate school since it is quite different from the norm in chemistry. So, our research and our approach are new to students when they first join the lab. With this selection process, I get what I get from a very good group of students. And most of the time I end up with terrific students. But in some ways it is not a rational process of selection…

Postdocs applied directly to a professor. Whitesides used two main criteria to sort through the many applicants each year. First, people had to demonstrate academic honors and a keen intellect. Second, they had to work well with others. Both criteria were equally important. They were used to assure a good fit with other lab members. Whitesides commented,

> Obviously one wants the best people one can find in terms of imagination and intellect, but I'm very much concerned with their ability to work with others, because everything we do in the laboratory is collaborative and this is a very important aspect of our lab culture. I also want postdocs to come with as broad a range of backgrounds as I can assemble. The philosophy behind the selection process is to have diversity in the postdocs and to have the best people that I can find as graduate students and then put them all together. My main concern is to make sure that they understand that they are all supposed to work on projects collectively. What usually comes out of that mixture of experience, youth, enthusiasm, different backgrounds, and basic pleasure of working in teams is a research group which is really able to do amazing stuff! We do not hire people for their ability to solve a particular problem. We hire people for their general ability and background: based on that, they can then create the problems within some broad constraints.

Douglas Weibel, a postdoc who had been working at the Whitesides Lab for over two years, talked about his decision to join the lab:

> I was familiar with George's work in a broad sense. I knew he had the reputation of taking people from different fields and allowing them to retrain or to broaden themselves. He had the reputation of then spitting them out as generalists, or as people who are comfortable working on interdisciplinary problems and across fields. He had the reputation of being an excellent scientist.

As soon as members joined the lab, Whitesides explained to them that the lab had one primary objective: *to fundamentally change the paradigms of science*. Whitesides explained what he meant:

> This means that the objective is not to publish papers. If we publish a paper or many papers that's all terrific, but the fundamental objective of the lab is to change the way in which people

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[2] "The new biochemphysicist," Discover Dialogue, *Discover*, December 2003, p. 22.

> think about research and think about the field that we are collectively in. Thus, if we work on something and 10 years later we find that no other people are working on that kind of research, or the techniques have not been promulgated, or the ideas have not extended beyond the lab, then our effort has been a failure. Our lab has to think about the problem in terms of something that will make a difference: the problem has to be interesting enough so that other people will think about working on it themselves. And the lab has also to think about the full spectrum of activities, which range from picking the problem to selling the solution at the end.

Whitesides saw that making an impact was the product of two vectors: the quality of papers coming out of the lab and quantity of papers. He explained,

> The reason is that you are not going anywhere unless you have good ideas but if you have one good idea only, and you publish one terrific paper, it usually disappears. A little bit of advertising to show how the content of the paper can be used is necessary. You have to disseminate the ideas in different communities and for each field you have to try to identify relevant examples and test cases where your research could be applied.

The approach to scientific discovery that Whitesides used was 'butterfly-like'. As he explained, "We move from flower to flower, into a problem with a fairly large number of people, work on it intensively for some years, and then move out into some other area."[3] 'Going after big ideas' was one of the lab's mottos. Many other academics saw this as high-risk research, especially for students and postdocs starting their careers. Yet, Whitesides held the opposite view:

> By working on problems that are original, you minimize risk. If you work on an important and interesting problem, you get a lot of credit since you are going off in a new direction and you are also showing something that is unexplored and neat. And this is true also in the case you solve only part of the problem… On the other hand, if you work on issues that are routine, nobody really cares whether you succeed or fail, and thus you get no credit in either case. This argument, I think, holds both at the university and in industry.

How Ideas are Generated and Work Gets Done

The lab used classical and state-of-the-art techniques to research topics at the boundaries between chemistry, biology, solid-state physics, and engineering. The lab was renowned globally for its publications, graduates, and creative concepts. Over 900 papers had been published, mainly in top journals such as *Nature*, *Science*, the *Journal of the American Chemical Society*, the *Journal of Organic Chemistry*, and the *Journal of Physical Chemistry* (see **Exhibit 6**). The publication process served as a powerful organizing and communication mechanism for the research results derived from the team projects conducted in the lab.[4] Teams varied in size but usually contained two to seven members. Two-member teams were rare. Nobody worked on a project alone except at its initiation. Each working group researched several themes, usually four to six, which were considered strategic thrusts: areas with potential for major discoveries. Teams were entrepreneurial, learned from others in the lab, and developed their own tactics for dealing with each new research problem, often without Whitesides' guidance. While the general research direction came from Whitesides, details were left to the lab members. Weibel commented,

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[3] "A marriage of nanotech and biotech," *BusinessWeek,* July 30, 2002, http://www.businessweek.com/technology/content/jul2002/tc20020730_2633.htm, accessed January 30, 2006.

[4] Most papers were published in journals that had rigorous peer-review processes and were assumed to critically evaluate both ideas and research methods.

> When I sought a position in the lab I contacted George by email and he replied by offering me a postdoc position that had just opened. George asked me to apply to the NIH for my own funding. I did so and asked him what areas he was interested in that I should consider writing a proposal on. He gave me a very broadly defined set of problems in the form of short phrases. For example, one was "mitochondria as reagents." And that was it. It was up to me to figure out what I wanted to work on and, at least, write a proposal. In the end, the proposal got funded by the NIH and luckily they haven't held me to that specific project: I've worked on everything but that project!

When new recruits joined the lab, they were usually presented with a list of 5 to 10 projects Whitesides thought were important. They were also given a summary of each lab member's research, and asked to spend considerable time in the lab talking to researchers, who were also eager to get help with projects and thus tried to sell their "hottest ideas" to new recruits. Based on the list and others' ideas, new students had the opportunity to decide what to work on. Often, for the first six months, new members just talked to lab members and explored potential projects where they could make a contribution—usually working with different groups on different ideas.

Team members were helpful to each other. They met regularly on formal and informal bases to discuss the status of their project, solve problems, and develop wild ideas. Nevertheless, Whitesides was adamant about results. A student needed to have three or four first-author papers, a few second-author papers, and a few third-author papers. Thus, by the time he or she left the lab, a student usually had 10 or more published papers or submitted manuscripts. A student's doctoral thesis was literally a bound collection of all her or his published papers and manuscripts. Whitesides commented on this unconventional approach, "We staple them together and that's the thesis. We do not even change it. I've told the department that there is no way I can disentangle the contribution of an individual student from these highly collaborative projects. And also I do not intend to. Finally, they accepted this approach. It is very clear that it is the group that collectively generates the ideas and does the work. It is equally clear that the group collectively gets the credit." Whitesides went on to explain why the delicate problem of authorship was not a problem in his lab:

> The way we deal with senior authorship works out naturally and everybody understands it. Plus, groups are so productive that there's not really a problem with people having lots of opportunities to be first author. I'm always the last author. The first author is the person who takes the intellectual responsibility at the end by pulling the whole thing together, by doing most of the writing and by getting the organization done. And usually students are very good at recognizing who has been the engine for making the project go. At the beginning, new students are often supporting authors, but, by the time they leave, they are usually first authors. In the end, I think people very much like this notion of cooperation in research and the idea of research as a social as well as scientific activity. It is just fun to work with smart people on interesting problems!

All the lab members generally shared Whitesides' view on authorship, considering it a "very generous policy" and a "very good system." Once a paper was written and submitted, the lead author provided documents to recipients on a checklist. A printout of the paper was sent to Harvard's Office of Trademark and Technology Licensing (OTTL). The official patent policy of the university stated that it was the responsibility of every member of a group who worked for the university to report his or her inventions to OTTL. The office was responsible for deciding whether it had commercial value. Whitesides was involved in the decision process as well. When he thought an idea had particular commercial relevance, he made sure it got the deserved attention. OTTL's Robert Benson commented:

> Probably half of my work comes from George's group, both in terms of patenting and licensing. The way I've worked it out with George is that he just sends me every manuscript at the time he sends it off to a journal. These are triaged in terms of filing patent applications. Some are commercially relevant; for these, I make contact with the lead author since George is often not available, and I make decisions about filing. Others, such as review papers, are not commercially relevant. For those in the middle I email George for his opinion—he is very honest.

The Lab Organizational Structure

There is nothing unique about what we do. If you asked me what the most unusual characteristic of the research group was, I would put my emphasis on the people. I have no doubt that the creative center of the group is the students. In this respect we are very different from all those university research groups which are focused on the leading idea of one professor, one student, one idea, or one thesis.

—Professor George Whitesides

Whitesides' approach to managing the lab emphasized collaboration and teamwork. There was a lot of "cross-pollination" and mobility across groups within the lab. As Weibel described the culture,

> This group gets along phenomenally well for a group that is full of very bright, very ambitious people who come from lots of different backgrounds. This group is designed in a way that there are no conflicts with people doubling up on projects and competing with each other. People are really open to speaking to each other. And it is very easy to weed out bad ideas if you are talking to people about them. I find that absolutely invaluable.

A research lab organization with a flat structure in which group members help each other on their projects did not need a lot of guidance. "I don't do any hand-holding," noted Whitesides. "Most of the meetings we have are meetings in groups. We have group seminars and we also have subgroup seminars. I talk to groups about specific problems, but since these projects are all collaborative, there are usually not a lot of reasons to talk to students individually. Students are very much on their own within the group to find resources within the group which can help them to solve things. I think what most of them say is that probably the thing they find most useful about being in a group is getting to know all the people." This flat structure pushed much of the responsibility to postdocs and doctoral students. Weibel noted,

> I had a meeting with George as soon as I joined the lab. He asked me what my goal in life was and what I wanted to do. We really didn't talk about research specifically. At a second meeting, I told him I was interested in energy. And he said, "Why don't you go build a fuel cell?" That was it. And that's pretty much the only direct command (or one of few) I've ever gotten from him on research.

The lab members admired Whitesides both for his research contributions and for what they learned from him. Lara Estroff, a postdoc, recalled:

> During the first month I was at the lab I met with George. He told me he was going to teach me how to be creative. His favorite line is that the best projects are those that you can think up one night in the shower, get into the lab the next day and in two weeks have all the experiments done and then get it on the cover of *Science*. I don't know if this has ever actually happened, but I think I have learned to force myself to think about how to make it happen. George has an unlimited supply of ideas and he has a sense of which direction to go. This is part of his continued influence on the lab.

In some respects, Whitesides was considered an unusual advisor. The prestige and fame resulted in lots of travel and he was often not in his office. And when he was there, his time was divided between lab members and university colleagues all vying for face time. However, Whitesides was very effective with email. Lara Estroff commented, "Through emails, George ends up being much more than a hands-off type of advisor. I get emails from him asking whether I've done the experiment we talked about, asking my take on a research idea. So, even though we hardly see him, he ends up being a pretty hands-on advisor and it amazes me that he can keep track of everything that's going on in the lab."

A lab bulletin circulated in the research group every quarter. Two bulletins contained short research summaries from every project: basically, the title of the projected paper, the authors, and a few sentences summarizing the content. Twice a year, researchers provided a more detailed description of their projects in the bulletins, and included data, charts, and photographs. The short version of the lab bulletin contained about 40 pages, while the semi-annual, long version was over 80 pages. As Weibel noted,

> The bulletins have multiple purposes. First, they keep George abreast of what everyone is working on. Second, and probably just as important, they keep everyone abreast with what everyone else is working on, so that there is no duplication. This approach also provides an easy way to figure out what projects you are interested in, projects you might want to collaborate on and contribute to.

From Bench Experiments to Published Research

Whitesides had a very well-defined structure of how a research paper should be written and how the internal review process should work. Weibel commented,

> As soon as you have one really interesting research result with your project, you write what's called an outline. You write basically a three- to five-page document that has bulleted points with the one result in it and the corresponding figures. It is formatted just like a journal article. And you put a cover page on it explaining what you've done. You put it into a folder. You label the folder in a certain way and put it in George's mailbox.

This paper creation cycle repeated itself over the duration of the project as new results were discovered and new drafts written, until the paper was published. This became the process for each team to report to Whitesides on a regular basis. Gudiksen explained:

> We have to prepare a draft for George that we receive back usually within one or two weeks with George's detailed comments. The review process is an important part of our work. If he has not seen a new version recently, you receive an email from George asking for it or, at least, for a good explanation for why the report is not yet in his mailbox.

Each new draft was put in a standardized folder, the cover of which indicated the title of the project, its authors, and a list of dates to track the project's progress, and placed in Whitesides' mailbox outside his office (see **Figure A**). Usually a letter preceded the draft, explaining details of the project or asking specific questions for Whitesides to answer, and specifying potential outlets for the paper. The same folder went back to the authors a week or two later with Whitesides' comments. His feedback included comments on the ideas, how they were executed, and the writing (see **Exhibit 7** for an example). Usually, around 10 iterations of this type occurred during the life of a project before the paper was ready to submit to a journal. Project termination was rare; when a specific research idea became uninteresting or ran into too many dead-ends, projects were redirected within the same research area.

Figure A Whitesides' Mailbox

Source: Casewriters' research.

Almost all projects were multidisciplinary, as reflected in the wide range of researchers' backgrounds. Researchers emerged as generalists (see **Exhibit 8** for information on the career paths of lab members from 2001 to 2005), learned in how to carry out multidisciplinary and multi-investigator research, and in how to communicate the results effectively. Whitesides reflected on the need for a wide-scale change in science research from narrow studies within a single discipline such as biology, chemistry, or physics to a new paradigm that required deep knowledge of all three: "We need to make a system that provides positive incentives—money, places to publish, etc. - and removes disincentives—so departments have to be tolerant and the community has to be interested in the work that comes out of the space between disciplines."

The emerging field of nanotechnology was such a field. Whitesides believed success in nanotechnology required a solid grasp of several core sciences. In his view, for example, biologists were masters at making nanomachines such as the light-harvesting apparatus of green plants, and thus it was important to understand biology so as to understand nature's design: "I would say that we need chemistry to make things, biology to teach lessons about what to make, materials science to use the materials, and physics to measure the properties. It is a multidisciplinary area." Further, he saw cross-disciplinary research as a new platform for teaching:

> If you try the multidisciplinary approach, you can teach thermodynamics just as well using the solid state as you can using liquid solutions. You can teach organic chemistry better with biology as a focus and with more interest than conventional organic synthesis. One should focus on the most interesting things and students are pretty canny about what's interesting and what's not interesting. They are more engaged in work that is current.

Whitesides also had ongoing collaborative projects with scientists[5] outside his lab, and continuing work with alums of the lab (see **Exhibit 9**). Usually outside collaborations were undertaken when specific expertise was needed, adding coordination costs to project budgets. As one member of the lab noted, "One of the virtues of having a big and diversified research group is that most of the skills that are needed on a project can often be found inside the lab."

The impact of the Whitesides lab ranged well beyond publication of first-rate research papers. A large number of graduates established their own outstanding research groups. As Art Ellis[6] noted, "George attracts outstanding individuals from around the world to his laboratories. Many of these individuals then start their own independent research groups and develop successful programs that further amplify the number of researchers being trained." University of Chicago chemistry professor Rustem Ismagilov reflected on what he learned at the Whitesides lab:

> I don't think many people appreciate how much time George spends on every paper. Each paper goes through 10 to 20 drafts before it is submitted. George reads each draft and provides exceptionally detailed feedback. He teaches people how to write. He teaches people how to think about what a conclusive experiment is. And he teaches people how to think about what the strong, important questions are. The review process he set up is very educational. In my research group, I do not do it as formally just yet, but I do emphasize how important it is to start thinking about formulating questions and hypotheses before doing the experiment, and not after having collected data and having analyzed them to realize that the main control experiment is missing and that the data are not conclusive. Following his example, I tell my students not to settle for the comfortable, simple thing that can be done. I tell them they should keep looking and thinking further.

Funding the Research

Following World War II, the U.S. federal government assumed the primary role for funding academic research in science and technology. Most academic labs had a mix of research grants and contracts from federal agencies in addition to some support from university and industrial sources. Some students and postdocs secured their own funding (mostly in the form of a fellowship to cover living expenses and fees), but it was the responsibility of the leader of the lab to provide funding for research through proposal writing. Most researchers found this to be time-consuming and onerous, yet many believed it was valid competition in the marketplace of ideas. No one found wide support for an alternative system.[7]

In 2005 four federal agencies provided the primary support to the Whitesides Lab: the National Science Foundation (NSF); the National Institutes of Health (NIH), which had grown rapidly as a primary funding source in the fields of biology and life sciences research; the Department of Defense

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[5] Examples of frequent collaborators were Don Ingber (Professor of Pathology at Harvard Medical School and Children's Hospital), Mara Prentiss (Harvard Professor of Physics), Howard Stone (Harvard Professor of Engineering and Applied Math), and Ralph Nuzzo (University of Illinois Chemistry Professor).

[6] Art Ellis was the Meloche-Bascom Professor of Chemistry at the University of Wisconsin-Madison and director of the Division of Chemistry at the National Science Foundation. Views expressed by Ellis were his own and did not necessarily reflect the views of the National Science Foundation.

[7] Most funds were directed to a principal investigator; however, a small number of large research grants came as "block funds" to mission-oriented research centers. These center grants were usually for a period of up to five years, with opportunities for renewal. In rare cases, labs or centers had endowments or other forms of private support to for continuity of research programs or for high risk and exploratory projects.

(DOD); and the Department of Energy (DOE)[8]. Although the lab consistently attracted funding (see **Exhibit 10** for data on yearly grant income), Whitesides worried about a funding process that undervalued creative ideas:

> We work in a peer review system. The trouble with peer review is that, by definition, a peer community is a kind of "averaging" device, and so the peer review process is a very good one for taking out bad ideas, and also a very good one for taking out unusual ideas. And the unusual category takes out a lot of the stuff that's really interesting and exploratory. As a result, one has to deal with a funding mechanism which rewards or supports the research that is obviously developmental and "correct."

A further concern related to the dominance of NIH, which funded about 65% of all academic research. Its approach to evaluating research proposals was to convene a panel of experts to rate a stack of submissions that, it was believed, favored "conventional wisdom and established researchers." Jeremy Knowles[9] described one consequence of this approach:

> There are really some frightening trends in the federal government's support. One of them has been known for several years and is represented by the disturbing increase in the average age of NIH grantees over the last two decades. It seems to me that our method of funding is increasingly supporting geriatrics instead of feeding those who take more creative risks, i.e., the young.

Since maintaining funding was so critical to the lab, students and postdocs were often involved in writing proposals for grants, an activity that consumed about 20% of the researchers' time, was often frustrating, and lacked transparency. Ellis described efforts at NSF (about 20% the size of NIH) to mitigate these criticisms:

> NSF funding operates by merit review. Individuals can send us unsolicited proposals in areas spanning science and engineering, and we assess proposal strengths and weaknesses by sending them out to peer reviewers around the world. Our program officers make recommendations based on the reviews and share them with the proposer, while protecting the identities of the reviewers. The program officer also provides constructive feedback to the proposers so that, especially in the case of a declined proposal, the investigator can craft a stronger proposal when he or she resubmits. The NSF statistics are somewhat discouraging in the sense that for new investigators - individuals who haven't been in the system before - the success rate is about 20%. For individuals who have awards and are submitting renewals, the success rate is better: In chemistry it's approximately 60% in a good year. Mentoring by experienced, successful faculty colleagues like George is an important part of helping investigators, particularly individuals who are new to the system; write proposals that can be recommended for funding.

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[8] A 2006 report in Science suggested that the federal governmental agencies that supported university research were requiring more stringent controls and audits of their grants and contracts, and gave much less flexibility to investigators in the conduct of research. The government's intent was to hold researchers and their institutions accountable to what was agreed in the original proposals (or as formally amended later). This held for which experiments and research topics were pursued as well as the allocation of a researcher's time to the project. For example, a 25% time commitment was not restricted to 25% of a 40-hour work week, but 25% of a researcher's total professional effort, which might be as much as 80 hours for many investigators. "U.S. Rules on Accounting for Grants," *Science*, 311 (January 2006): 168–169.

[9] Jeremy Knowles, Dean of the Faculty of Arts and Sciences at Harvard from 1991 to 2002, was a renowned chemist and academic leader who had known Whitesides since 1961 when he was a postdoc at Caltech, at the time Whitesides was doing his doctoral studies.

Ellis continued, "George has made the point, along with a number of others in the community; that NSF needs to be more adventuresome, that we have an important role in supporting work at the frontiers of science. A workshop George helped organize led to a new program in our division called Chemical Bonding Centers that represents an effort to address this concern. "

Perspectives on Whitesides

George has managed to put together epochs of work that have really shaped the content of big hunks of chemistry. He is an intensively curious person.

—Ralph Nuzzo, Professor at the University of Illinois[10]

By 2005, Whitesides had become one of the most visible members of the chemistry community. Knowles commented:

> When I first met him, George was a first-year graduate student at Caltech. He was somebody who not only knew all about the arcane corner of organic chemistry that I'd worked on; he also knew all about everything else as well. Already at that time, George was a marvelously eclectic man. And today, he is one of the most eclectic chemists on the planet. His intellectual range is quite extraordinary. His intellectual eclecticism is indeed his most extraordinary characteristic. He is a researcher who tackles major challenges fearlessly—a scientist who has always been interested in and concerned about practical applications of his research, an academic who has always been very interested in the world around him as well as [in] research projects that illuminate the underlying science. George is capable in a very interesting way of "shaking the cage."

Although Whitesides was officially a professor of chemistry and chemical biology at Harvard, he was viewed as "a Renaissance thinker whose ideas crisscrossed scientific disciplines, and an outspoken critic who was fond of reminding scientists that they really understood very little."[11] Mark Skaletsky[12] described Whitesides' role in developing substantive solutions to the problem of translating academic science: "George is a drill-down thinker. He will take an idea and just keep working it and working it and working it. He spends more time thinking about the solution as opposed to just the idea." Jim Tananbaum[13] described Whitesides as "extraordinarily good at generating creative, out-of-the-box ideas." He added, "George has a very clean and clear sense of whether once a problem is defined it could be technically met with what is currently available. He is very good at being realistic about what can be done and he is also extraordinarily clever. He is very good at relaxing all constraints. He is never in a box. He takes a problem and looks at it from every possible angle. He then generates solutions to that problem based upon the different ways of looking at it."

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[10] Ralph Nuzzo earned his doctorate degree while a student of Whitesides at MIT; Nuzzo then worked a number of years at AT&T Bell Labs before moving to a full professorship at the University of Illinois.

[11] "The new biochemphysicist," Discover Dialogue, *Discover*, December 2003, p. 22.

[12] Mark Skaletsky (CEO of Trine Pharmaceuticals) was a serial entrepreneur with experience in several biotech companies, notably Biogen Idec, Enzytech, and GelTex.

[13] Jim Tananbaum (managing director, Prospect Venture Partners), who held M.D. and MBA degrees from Harvard, was a cofounder with Whitesides of GelTex and Theravance.

Whitesides' accomplishments added up to a long list of groundbreaking contributions (see **Exhibit 11** for Whitesides' publications)—from bioengineering, in which he developed methods to use catalysts (enzymes) from cells to facilitate organic synthesis, to the field of microfluidics. Whitesides' research spanned a broad spectrum of disciplines, from biochemistry to materials science. Over the years, much of his work remained in areas with implications for biotechnology: self-assembling molecules to make nanomachines, polyvalent drugs to attack disease from multiple directions, and new analytical tools for drug discovery. More recently, his work focused on nanotechnology. Whitesides' research could readily be applied to practical problems: "George has a very broad view of science and technology, and has appreciated what basic research can do to inform new kinds of applications," Art Ellis explained, "and he and his coworkers have often published what might be called proof-of-concept experiments that demonstrate how something they did in basic research can be applied in some areas of technology."

Scientists spurned efforts to quantify their contributions, and Whitesides himself was particularly guarded about applying quantitative measures.[14] For example, few people knew he was intimately involved in founding over a dozen companies. Whitesides was highly sought as an advisor to large firms, startups, and government agencies, too. Further, he was ranked the number-one chemist in the ISI web-based research evaluation tool, "Essential Science Indicators," with more than 10,000 citations to his credit since 1991 (see **Exhibit 12** for data on citation frequency).[15] He was the author of over 70 papers that had been referenced more than 100 times each, while his classic article, titled "Formation of monolayer films by the spontaneous assembly of organic thiols from solution onto gold" (C.D. Bain, et al., *Journal of the American Chemistry Society* 111(1): 321–335, 1989) had been cited well over 1,400 times (see **Exhibit 13** for Whitesides' most-cited papers published since 1992). As noted by Knowles, researchers in the sciences often got cited because they published a paper on an ordinary method or technique with widespread use. "Often the citation indices don't quite capture the intellectual," he noted, "but if George is the most cited chemist over the last number of years, it is because of his breakthrough research. He's not a banal methodologist."

Whitesides was always furiously busy but never missed his teaching responsibilities, even undergraduate lectures. As Knowles noted, "For all his extraordinary range of activities, he is absolutely scrupulous about his teaching. He designs new courses, he co-teaches with interesting colleagues, and he was an attentive Chair of Department in the late 80s." Knowles continued, "George works with enormous penetrating energy. Whenever he says he'll do something, it gets done with extreme intelligence and persistence. Whitesides was a strong believer that researchers had to answer the big questions in science if they wanted to have an impact in what they did. When describing himself and his role in the research lab he was leading, he noted,

> I am part of the research group and certainly a very important part. But there is a lot going on in the lab that is very relevant in terms of our creative output in which I'm only facilitating and I'm not being the creative center. Students in the lab are young. They have time. They have all kinds of motivation. They have great ideas. And setting up the group in such a fashion that you take advantage of these enormously smart kids is a conscious effort in the way I run the lab. I think my approach is different from what other people do. But, aside from that, it is also something anybody can learn to do.

---

[14] The advancement of science was based on critical assessment of the work of others, yet there was an avoidance of value judgments such as the statement by Nobel laureate, Julius Axelrod: "Ninety-nine percent of the discoveries are made by one percent of the scientists," *Proceedings of the American Philosophical Society*, vol. 149, no. 2, June 2005.

[15] "Harvard's George Whitesides on Nanotechnology: A Word, Not a Field," *ScienceWatch*, July/August 2002, http://www.sciencewatch.com/july-aug2002/sw_july-aug2002_page3.htm, accessed January 30, 2006.

The Commercialization of Ideas

Although Whitesides tried to confine his research to breakthrough science, a smaller complementary effort created intellectual property (see **Exhibits 14** and **15**) to facilitate the commercialization of the lab's research products; this represented only a part of the transfer of original work to industry, however. Whitesides had cofounded a dozen companies, for which his role was not just to supply the original science to start the company, but also to provide advice for the ongoing development of the underlying technology and applications. Some startups were founded on intellectual property (IP) from his lab (often by lab graduates), while others were founded, in whole or in part, on the original ideas and broad concepts that came from Whitesides' inventive mind. Examples of the latter sort included Genzyme, Geltex Pharmaceuticals, and Advanced Magnetics. Examples of startups more directly connected to the lab's IP were Theravance, Surface Logix, Nano-Terra, and Claros Diagnostics.

Carmichael Roberts[16] explained,

> There are physical things as well as ideas that spin out of George's lab. In the case of GelTex, it was an idea that was based on some broad, fundamental scientific work that George was doing, but there was never any direct work done on a polymer in George's lab. George believed that the engineering of materials and figuring out how to design the surfaces of them to interact with things in biology were important. GelTex made all of the materials and the direction came out of George's head, but was never done in his academic lab; but the basic science that one would need to understand it was.

The scale and scope of Whitesides' Lab provided a plethora of science concepts. This was possible since ideas in his lab were generated very quickly. Bryan Roberts[17] commented, "One of the foundations for biomedical progress in the U.S. in general, and George specifically, is the government's funding of really basic research. Large-scale funding of basic research is, in my view, very important in stimulating innovation. One may not immediately see what the commercial application will be, but basic research provides the infrastructure for advances that result in commercially relevant products." People who founded businesses with Whitesides described him as a person who was frequently the source of initial and ongoing ideas that brought scientific solutions to commercial problems; he was outstanding at taking complicated problems and simplifying them. "With GelTex," Tananbaum (Prospect Venture Partners) noted, "once a problem was defined, George generated dozens and dozens of possible solutions."

Tananbaum was involved in a second startup based on broad ideas whose IP came only after the company was founded: "George and I had talked for years about multivalency, which became the underlying science for Theravance." With Tananbaum and Burt Christensen[18] filling key leadership roles, the company was founded in 1997 and began developing specific applications of what was originally just a scientific concept.

In terms of return to investors over the last 10 years in healthcare, GelTex and Theravance were viewed as very successful startups (e.g., GelTex was acquired by Genzyme for $1.6B in 2000).

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[16] Carmichael Roberts, president and cofounder of Surface Logix, had been a postdoc in the Whitesides lab and also obtained his MBA degree from MIT's Sloan School.

[17] Bryan Roberts (Venrock Associates, general partner since 2000) spent three years in investment banking before getting a Ph.D. in chemistry at Harvard. After earning his Ph.D. degree, he won a Kaufman Fellowship to intern in venture capital.

[18] Burt Christensen was the retired head of R&D at Merck Pharmaceuticals. Whitesides and Roy Vagelos, Merck's former CEO, also served as company directors.

Whitesides was unusual as a scientist because he was comfortable around leaders of business and science. He maintained contacts with a large number of executives and research scientists throughout the world. Carmichael Roberts described the value of Whitesides' name in opening doors when they created Surface Logix and moved it from a concept to a startup with customers and a plan:

> Having an opportunity to work with George is a gift in itself, but beyond that, George was the source of industry contacts [for business development, customers, contracts, and recruitment]. George came to me with a stack of business cards; it must have been . . . 50 or 60 business cards from different people in different industries. And he said to me, "Carmichael, these are all the people who have tried to talk to me over the last couple of years about ways to work with the lab, and work with this technology to develop products for their companies. See who's serious and who's not, and what's interesting, and what's not."

Looking Forward: A Replicable Model?

I don't think it is money or facilities that make this lab work so well. Without them, it clearly couldn't function, but the success of the lab comes from George and from the way the lab is set up.

—Katie Drake Gudiksen

President Summers saw Harvard University at a critical juncture in its history. How should Harvard's faculty look at the opportunities to expand the impact of science? Was replicating the Whitesides model desirable? If so, was the lab scaleable to large mission-oriented centers? In looking to the future, the words Whitesides used to describe his view of science were difficult to forget:

> One unstated objective of science is to *make a difference*: to learn something, or make something, that changes the way people think or behave. Many of the biggest discoveries—the most important scientifically, and the most consequential socially—are surprises, and their consequences are unimaginable at the time they are made. Who would have predicted the changes in society that have come from classification of the elements into the periodic table, or from quantum mechanics, or the World Wide Web? Who could have guessed that the first NMR spectrum of ethanol would grow into the ability to watch the brain think? The unpredictability of these big surprises makes us timid in our speculations: it is embarrassing to be publicly wrong, and big surprises make dunces of us all. But, avoiding speculation makes science dreary and neglects our responsibility to society to warn of change even as we cause it.[19]

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[19] George M. Whitesides, "Assumptions: Taking Chemistry in New Directions," *Angew. Chem. Int. Ed.* 43 (2004): 3632–3641.

Exhibit 1 Biographical Information: Professor George Whitesides

George M. Whitesides, born in Louisville, Kentucky, received an A.B. degree in chemistry from Harvard University in 1960 and a Ph.D. degree from the California Institute of Technology in 1964. He was a faculty member of the Massachusetts Institute of Technology from 1963 to 1982. He joined the Department of Chemistry of Harvard University in 1982, where he served as department chairman from 1986 to 1989 and Mallinckrodt Professor of Chemistry from 1982to 2004, after which he became the Woodford L. and Ann A. Flowers University Professor.[a]

Whitesides received numerous accolades for his research, including the National Medal of Science in 1998 and eight awards from the American Chemical Society. Recently he received the Materials Research Society's Von Hippel Award (2000) as well as the prestigious Pittsburgh Analytical Chemistry Award (2003). Whitesides' work on functional nanostructures, termed "self-assembled monolayers," was top-ranked among citations in chemistry. His current research is multidisciplinary, encompassing areas of cell biology, biochemistry, chemical catalysis, and materials science. A member of the National Academy of Sciences, Whitesides also held advisory positions for many scientific organizations, including the National Research Council and the National Science Foundation.

Awards

- Alfred P. Sloan Fellowship (1968)
- American Chemical Society (ACS) Award in Pure Chemistry (1975)
- Arthur C. Cope Scholar Award (ACS) (1989)
- Arthur C. Cope Award (ACS) (1995)
- National Medal of Science (1998)
- Von Hippel Award (Materials Research Society) (2000)
- Doctorate Honoris Causa, University of Twente (The Netherlands) (2001)
- Kyoto Prize for Advanced Technology (Inamori Foundation) (2003)
- Paracelsus Prize (Swiss Chemical Society) (2004)
- Jacob Heskel Gabbay Award in Biotechnology and Medicine (Jacob and Louise Gabbay Foundation) (2004)
- Dan David Prize (Dan David Foundation) (2005)
- Welch Foundation Award (2005)

Memberships and Fellowships

American Academy of Arts and Sciences, National Academy of Sciences, National Academy of Engineering, American Philosophical Society, Fellow of the American Association for the Advancement of Science, Fellow of the Institute of Physics, New York Academy of Sciences, World Technology Network, Foreign Fellow of the Indian National Science Academy, Honorary Member of the Materials Research Society of India, Honorary Fellow of the Chemical Research Society of India, and member of the Royal Netherlands Academy of Arts and Sciences.

Recent Advisory Positions

- National Research Council: Board on Chemical Sciences and Technology (1984–89; Chairman, 1986–99); Naval Studies Board (1989–97; Vice Chairman, 1992–97); Committee on Bioprocess Engineering (1991–92); Board on Science, Technology and Economic Policy (1991–97); Visiting Committee on Advanced Technology (1994–97); Board on Physics and Astronomy (1997–2001); Committee on Science and Technology for Countering Terrorism (2002); Committee on Nanotechnology for the Intelligence Community (2003); Committee on Prospering in the Global Economy (The "Gathering Storm" Committee, 2005); Committee on Science, Engineering, and Public Policy (COSEPUP, 2005 and ongoing, chairman)

- National Science Foundation: Chemistry Advisory Committee (1984–86; chairman, 1986), Materials Research Advisory Committee (1991–93; chairman, 1993), Review Panel for the Materials Research Laboratories (1993, co-chairman); Advisory Committee for Mathematics and Physical Sciences (1993–96); NSF Senior Assessment Panel: International Assessment of U.S. Mathematical Sciences (1997); Workshop on Chemical Bonding Centers (2003)

- Department of Defense: Defense Advanced Research Projects Agency Defense Science Research Council (1984–); Defense Science Board (1993–2003); Threat Reduction Advisory Committee to the Defense Threat Reduction Agency (1998–)

- National Aeronautics and Space Administration (NASA): Biological and Physical Research Maximization and Prioritization (REMAP) Task Force (2002)

- Other: Scientific Advisory Committee for the Scripps Research Institute (1993–); Sandia Science and Technology Advisory Board (2002–); Intelligence Science Board (2003); International Committee to Assess the Status of Chemistry in the UK (EPSRC, 2003; chairman)

Source: Whitesides Lab website, http://gmwgroup.harvard.edu/domino/html/webpage/homepage2.nsf/HOME?OpenFrameSet, accessed August 16, 2005.

[a] The title "University Professor "was the most prestigious honor bestowed on a faculty member at Harvard University.

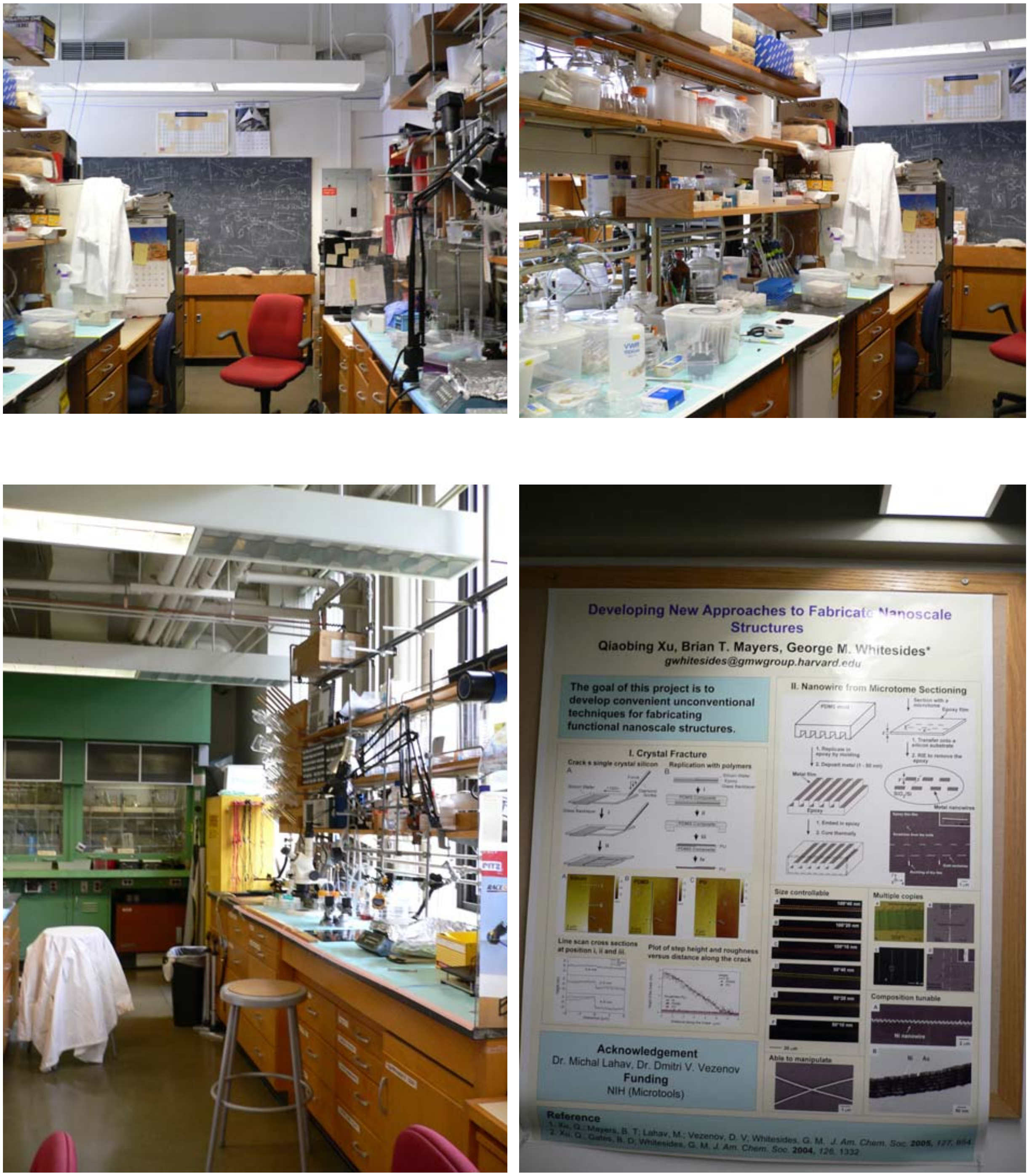
Exhibit 2 Description of Research at the Whitesides Lab (2005)

Research in the Whitesides Lab was based on four areas of disciplinary knowledge: biochemistry, materials science, catalysis, and physical organic chemistry. Each area required development of the fundamental skills of experimental chemistry—synthesis and characterization of new compounds, and examination of relations between molecular structure and reactivity or physical properties—but each, in addition, required skills in other research techniques: surface spectroscopy, microbiology, electron microscopy, ellipsometry, reactor design, and measurement of physical properties. The group was eclectic and generalist in its approach: at different times research on a particular problem may have required organic synthesis, organometallic chemistry, spectroscopy, computer analysis, biochemistry, molecular biology, or a wide range of other techniques.

Specific foci of the research varied widely. Work in biochemistry centered on adhesion of mammalian cells, viruses, and bacteria to surfaces, polyvalency, and rational drug design, and biophysical studies centered around capillary electrophoresis and surface plasmon resonance spectroscopy. Those concerned with work in materials science were occupied with the fabrication of nanostructures, microfluidic systems, microelectromechanical systems, and 3-D microstructures. The synthesis and characterization of structurally well defined organic surfaces (especially using self-assembled monolayers) and solids, and the use of these assemblies to study physical properties such as wettability and biocompatibility, were important components of this work. This area also included studies in physical optics and unconventional methods of lithography (e.g., soft lithography and various forms of near-field optical lithography). Much of the work in catalysis was directed toward fuel cell development. Problems in physical organic chemistry addressed issues in self-assembly, especially using mesoscale systems (objects with dimensions from 10 μm to 10 mm, held together by capillary and/or magnetic forces). Computation and simulation were also important tools in the group.

Source: Whitesides Lab website, http://gmwgroup.harvard.edu/domino/html/webpage/homepage2.nsf/HOME?OpenFrameSet, accessed August 16, 2005.

Exhibit 3 The Whitesides Lab: Pictures



Developing New Approaches to Fabricate Nanoscale Structures

Qiaobing Xu, Brian T. Mayers, George M. Whitesides*

gwhitesides@gmwgroup.harvard.edu

The goal of this project is to develop convenient unconventional techniques for fabricating functional nanoscale structures.

I. Crystal Fracture

Crack a single crystal silicon

Replication with polymers

Line scan cross sections at position i, ii and iii.

Plot of step height and roughness versus distance along the crack

II. Nanowire from Microtome Sectioning

Size controllable

Multiple copies

Composition tunable

Able to manipulate

Acknowledgement

Dr. Michal Lahav, Dr. Dmitri V. Vezenov

Funding

NIH (Microtools)

Reference

1. Xu, Q.; Mayers, B. T.; Lahav, M.; Vezenov, D. V.; Whitesides, G. M. *J. Am. Chem. Soc.* **2005**, *127*, 854
2. Xu, Q.; Gates, B. D.; Whitesides, G. M. *J. Am. Chem. Soc.* **2004**, *126*, 1332

Source: Casewriters' research.

Exhibit 4 Recent Performance Data for the Whitesides Lab

	2001	2002	2003	2004	2005
Grant Funding ($ millions)	2.0	2.5	3.1	3.2	2.9
Patents	5	4	7	11	4
Publications	48	56	43	29	9

Source: Grant funding and publications adapted from lab records. Patent data from the U.S. Patent and Trademark Office, http://www.uspto.gov/patft/index.html, accessed August 22, 2005.

Note: Data for 2005 represents a partial year.

Exhibit 5 Additional Lab Data for 2004

Staffing Levels	
Graduate Students	23
Post docs and Visiting Scholars	18
Administrative and Clerical Support	5
Square feet of lab space	6,000

Source: Adapted from lab records.

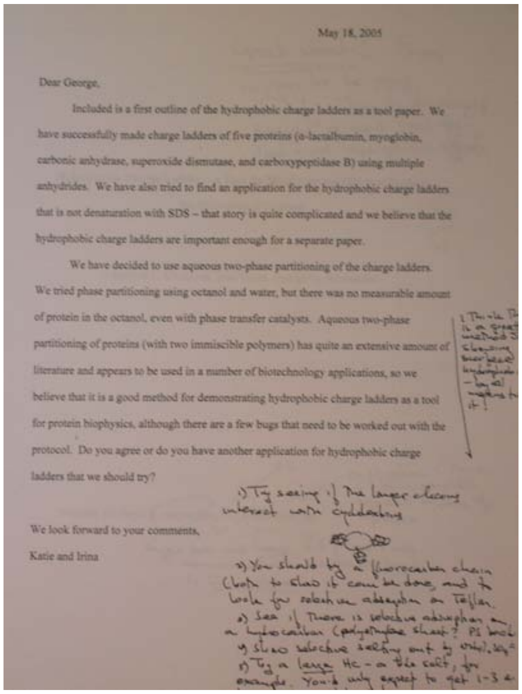
Exhibit 6 Selected Journals in Which Whitesides with Co-authors Published Research

Journal Title	Number of Articles
Analytical Chemistry	35
Angewandte Chemie (International Edition.)	21
Applied Physics Letters	30
Bioorganic Chemistry	7
Journal of American Chemistry Society	233
Journal of Medical Chemistry	10
Journal of Organic Chemistry	77
Journal of Physical Chemistry	15
Macromolecules	6
Nature	8
Organometallics	7
Proceedings of National Academy of Science	16
Science	33

Source: Adapted from lab records.

Note: As of August 2005, Whitesides had authored or co-authored over 900 papers and textbook chapters. His papers had appeared in over 120 academic journals.

Exhibit 7 Example of an Early Paper Draft and Whitesides' Feedback



May 18, 2005

Dear George,

Included is a first outline of the hydrophobic charge ladders as a tool paper. We have successfully made charge ladders of five proteins (α-lactalbumin, myoglobin, carbonic anhydrase, superoxide dismutase, and carboxypeptidase B) using multiple anhydrides. We have also tried to find an application for the hydrophobic charge ladders that is not denaturation with SDS – that story is quite complicated and we believe that the hydrophobic charge ladders are important enough for a separate paper.

We have decided to use aqueous two-phase partitioning of the charge ladders. We tried phase partitioning using octanol and water, but there was no measurable amount of protein in the octanol, even with phase transfer catalysts. Aqueous two-phase partitioning of proteins (with two immiscible polymers) has quite an extensive amount of literature and appears to be used in a number of biotechnology applications, so we believe that it is a good method for demonstrating hydrophobic charge ladders as a tool for protein biophysics, although there are a few bugs that need to be worked out with the protocol. Do you agree or do you have another application for hydrophobic charge ladders that we should try?

I think this is a great method for showing surface hydrophobicity — [illegible] making [illegible] it!

We look forward to your comments,

Katie and Irina

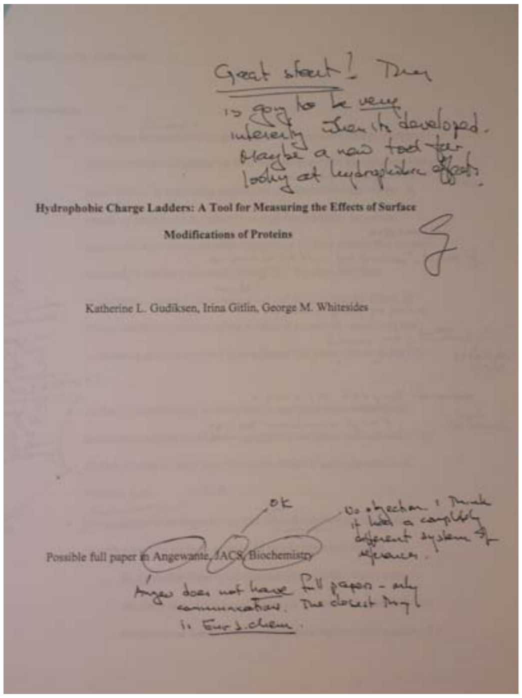
1) Try seeing if the longer chains interact with cyclodextrins

2) You should try a fluorocarbon chain (both to show it can be done, and to look for selective adsorption on Teflon.

3) See if there is selective adsorption on a hydrocarbon (polyethylene sheet? PS [illegible]

4) Show selective salting out by $(NH_4)_2SO_4$

5) Try a large HC – [illegible], for example. You'd only expect to get 1-3 a



Great start! This is going to be very interesting when it's developed. Maybe a new tool for looking at hydrophobic effects.

G

Hydrophobic Charge Ladders: A Tool for Measuring the Effects of Surface Modifications of Proteins

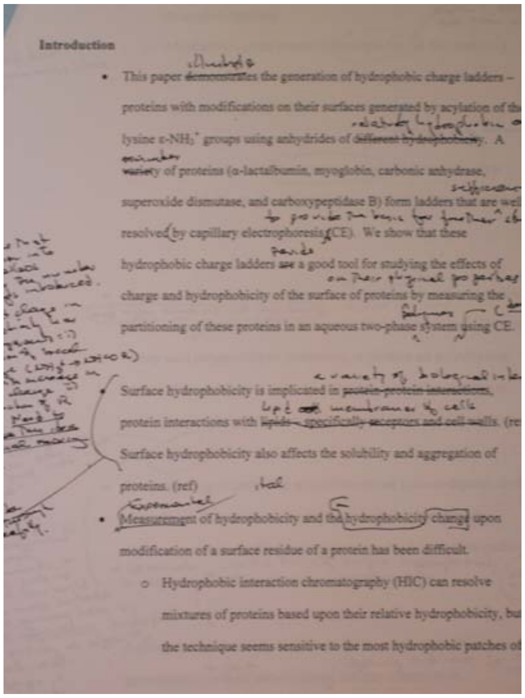
Katherine L. Gudiksen, Irina Gitlin, George M. Whitesides

ok

No objection. I think it has a completely different system of referees.

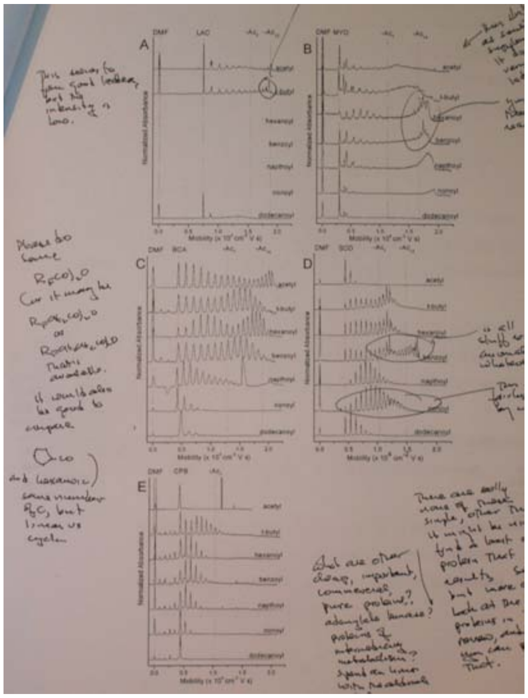
Possible full paper in Angewante, JACS, Biochemistry

Angew does not have full papers – only communications. The closest thing is Eur J. Chem.



Introduction

- This paper ~~demonstrates~~ describes the generation of hydrophobic charge ladders – proteins with modifications on their surfaces generated by acylation of th lysine ε-NH_3^+ groups using anhydrides of ~~different hydrophobicity~~ relatively hydrophobic a. A ~~variety~~ number of proteins (α-lactalbumin, myoglobin, carbonic anhydrase, superoxide dismutase, and carboxypeptidase B) form ladders that are wel sufficiently resolved (by capillary electrophoresis (CE)) to provide the basis for further [illegible] We show that these hydrophobic charge ladders ~~are~~ provide a good tool for studying the effects of charge and hydrophobicity of the surface of proteins on their physical properties by measuring the partitioning of these proteins in an aqueous two-phase system [illegible] using CE.
- Surface hydrophobicity is implicated in ~~protein-protein interactions,~~ a variety of biological i protein interactions with ~~lipids – specifically receptors and cell walls~~ lipid membranes of cells. (re Surface hydrophobicity also affects the solubility and aggregation of proteins. (ref)
- Experimental Measurement of hydrophobicity and the hydrophobicity change upon modification of a surface residue of a protein has been difficult.
  - Hydrophobic interaction chromatography (HIC) can resolve mixtures of proteins based upon their relative hydrophobicity, bu the technique seems sensitive to the most hydrophobic patches of



This seems to give good ladders, but the intensity is low.

Please do some $R_F(CO)_2O$ (or it may be $R_F CH_2 CO)_2O$ or [illegible] that's available.

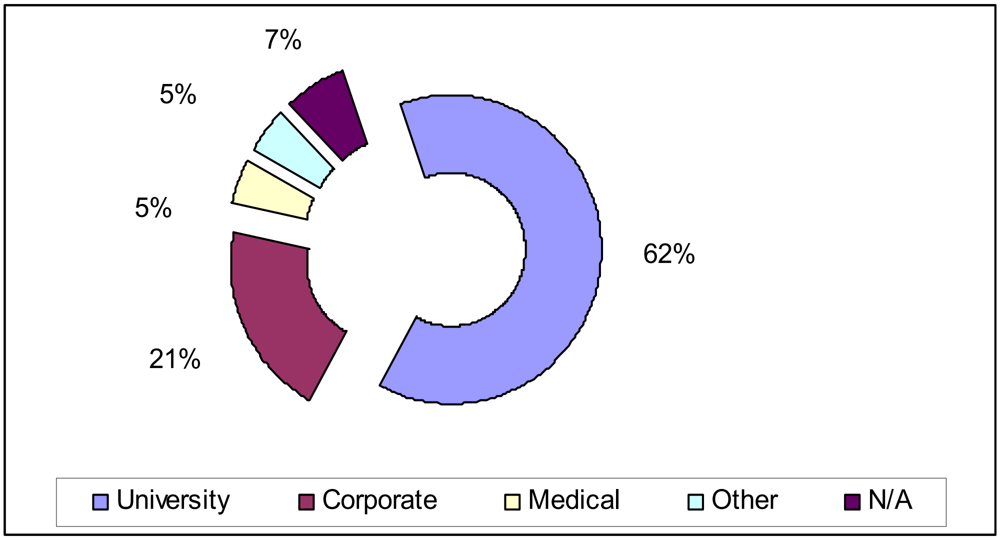
It would also be good to compare [illegible] and hexanoic (same number of C, but linear vs cyclic)

What are other cheap, important, commercial, pure proteins? adenylate kinase? proteins of intermediary metabolism? Spend an hour with the catalogs

These are early ones of these simple, other [illegible] it might be [illegible] find at least one protein that [illegible] but more [illegible] look at the proteins in [illegible] then can [illegible] that.

Source: Casewriters' research.

Exhibit 8 Career Paths for 105 Researchers from the Whitesides Lab (2001–2005)



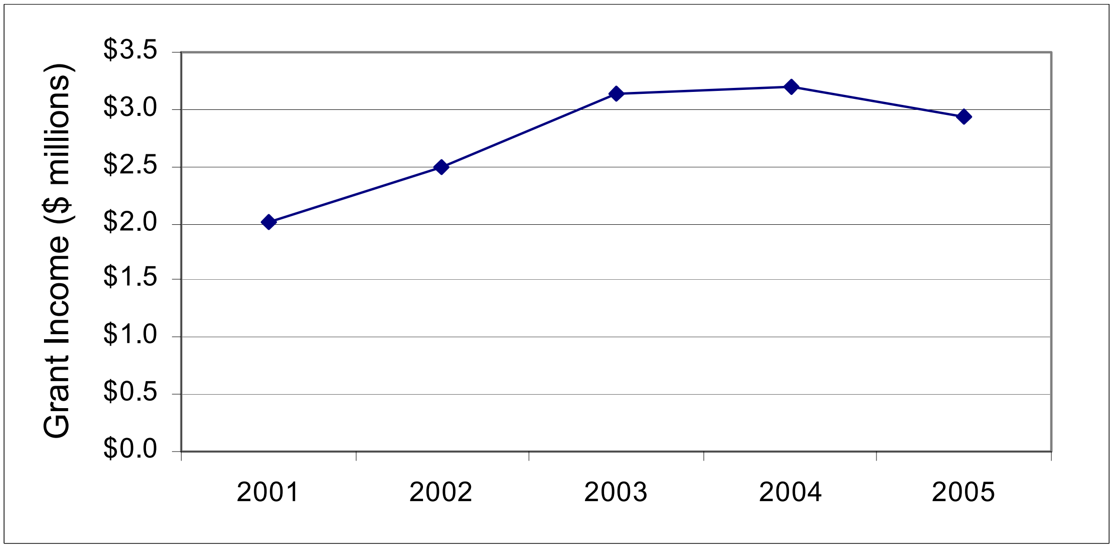
Source: Adapted from lab records.

Exhibit 9 Selected List of Whitesides' Most Productive Student Collaborators

Collaborator	Number of Publications	Number of Patents	Current Title and Affiliation
Bain, C.D	17	0	Professor of Physical Chemistry Laboratory; University of Durham, U.K.
Biebuyck, H.A.	28	2	Researcher, Igen, Inc.
Bowden, Ned	19	1	Assistant Professor, University of Iowa
Brittain, Scott	19	3	Research Scientist, Shire Labs
Chen, C.S.	17	0	Associate Professor, University of Pennsylvania
Folkers, J.P.	14	0	Research Scientist, Videojet Inc.
Gao, Jinming	16	0	Professor, University of Texas at Arlington
Grzybowski, Bartosz	25	0	Assistant Professor of Chemical and Biological Engineering, Northwestern University
Ismagilov, R.F	12	2	Professor, University of Chicago
Jackman, Rebecca	21	9	Commonwealth School
Jiang, Xingyu	13	0	Assistant Professor, National Center for Nanoscience, Beijing
Kim, Enoch	27	6	Surface Logix Corporation
Laibinis, P.E.	20	1	Professor of Chemical Engineering, Vanderbilt
Love, John C.	22	0	Postdoctoral Fellow, Harvard Medical School
Mammen, M.	16	0	Theravance
Mrksich, M	22	6	Professor, University of Chicago
Paul, Kateri	22	1	Nomadics, Inc.
Qin, Dong	15	1	University of Washington
Rogers, John	20	4	Professor, University of Illinois
Schueller, Oliver	16	4	Surface Logix Corporation
Seto, C.T.	17	0	Professor, Brown University
Simanek, E.E	20	0	Professor, Texas A&M University
Simon, E.S.	18	0	Rohm & Haas Corporation
Stroock, Abraham	17	0	Cornell Univ.; Asst. Prof., Chemical & Biomolecular Engineering
Tien, Joe	16	0	Assistant Professor, Boston University
Wong, C.F.	19	1	Professor of Chemistry, Scripps Research Institute
Xia, Younan	41	7	Professor, University of Washington
Xu, Bing	15	0	Professor of Chemistry, Hong Kong University

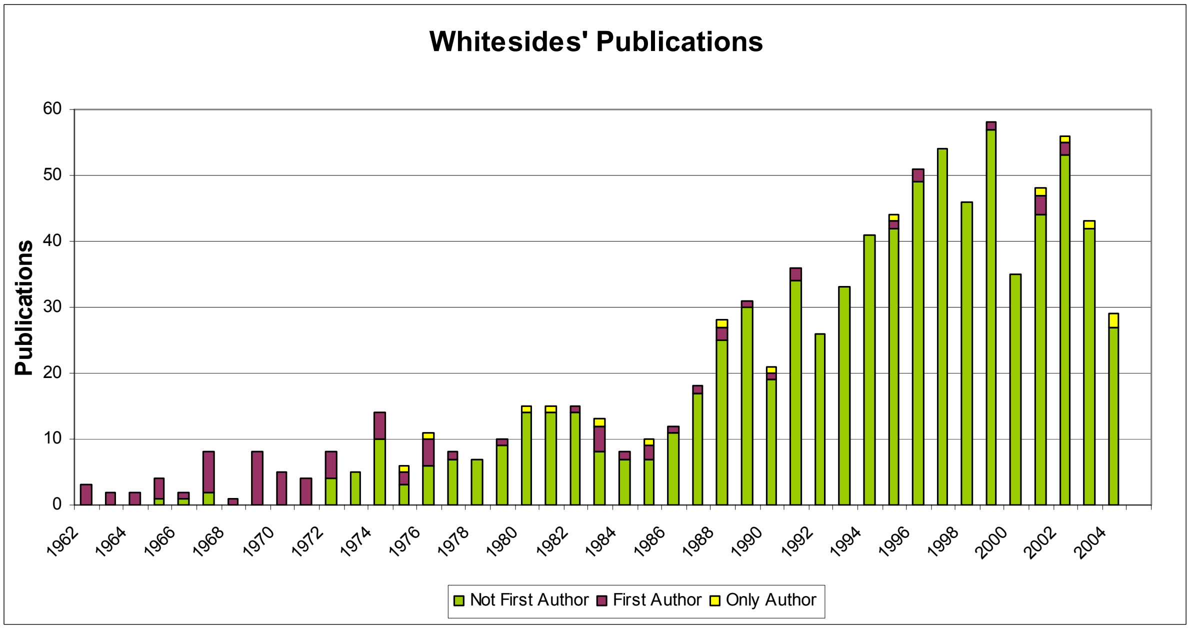
Source: Adapted from lab records.

Exhibit 10 Yearly Grant Income



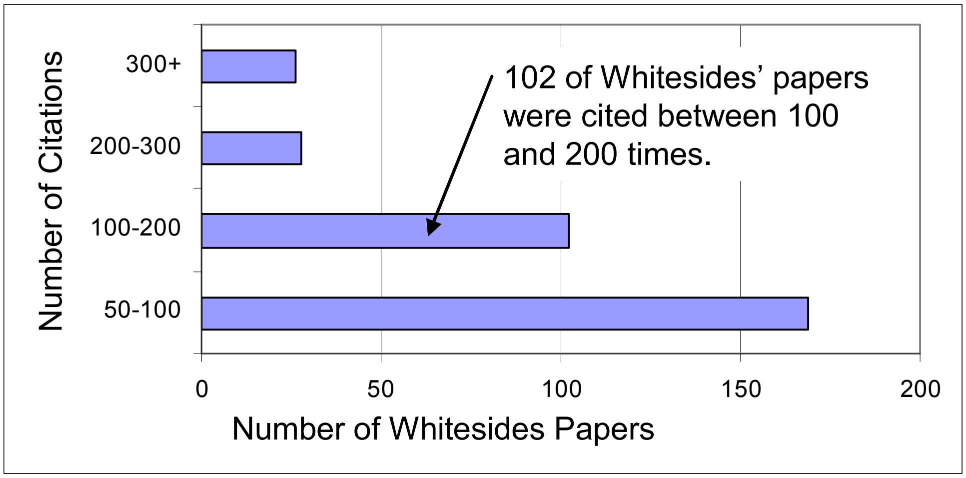
Source: Adapted from lab records.

Exhibit 11 Whitesides' Publications



Source: Adapted from lab records.

Exhibit 12 Citation Frequency



Source: Adapted from ISI Web of Science http://isiwebofknowledge.com (accessed August 18, 2005).

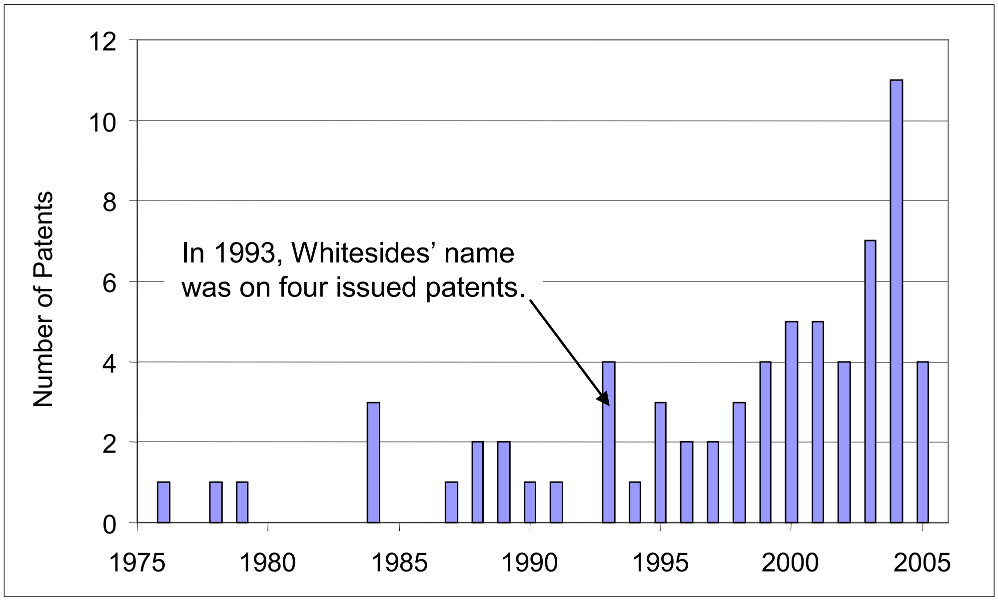
Note: Whitesides has had 858 papers cited—76 papers as first author and 782 other papers. His most cited paper as first author, published in *Science* in 1991, was cited 1,175 times. His most cited paper as a co-author was published in 1989 in the *Journal of the American Chemical Society* and cited 1,894 times. Overall, Whitesides' papers had been cited by other scientific papers over 60,000 times.

Exhibit 13 Most cited Papers by George M. Whitesides, Published since 1992 (Ranked by Total Citations)

Rank	Paper	Total Citations
1	C.S. Chen, et al., “Geometric control of cell life and death,” *Science*, 276 (5317): 1425–8, 1997.	420
2	A. Kumar, H.A. Biebuyck, G.M. Whitesides, “Patterning self-assembled monolayers: Applications in material science,” *Langmuir*, 10 (5): 1498–1511, May 1994.	382
3	Y.N. Xia, G.M. Whitesides, “Soft lithography,” *Angew. Chem. Int. Ed.*, 37(5): 550–75, 16 March 1998.	371
4	G.M. Whitesides, et al., “Noncovalent synthesis: Using physical organic chemistry to make aggregates,” *Acc. Chem. Res.*, 28(1): 37–44, 1995.	352
5	A. Kumar, G.M. Whitesides, “Features of gold having micrometer to centimeter dimensions can be formed though a combination of stamping with an elastomeric stamp and an alkanethiol ink followed by chemical etching,” *Appl. Phys. Lett.*, 63(14), 2002–4, 4 October 1993.	318
6	J.C. MacDonald, G.M. Whitesides, “Solid-state structures of hydrogen-bonded tapes based on cyclic secondary diamides.” *Chem. Rev.*, 94 (8): 2383–420, December 1994.	292

Source: ISI *Web of Science*, 1991–2001.

Exhibit 14 Number of Patents Issued with Whitesides as a Co-inventor

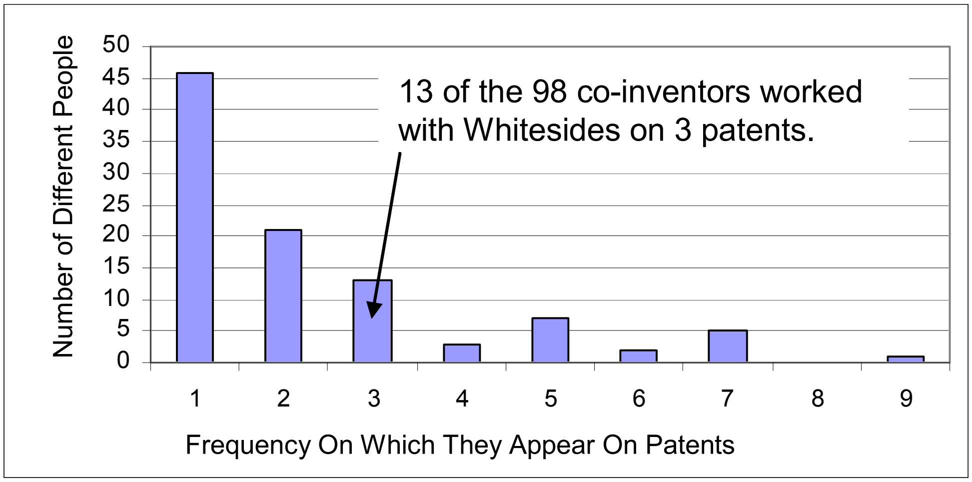


Source: Adapted from data from the U.S. Patent and Trademark Office— http://www.uspto.gov/patft/index.html> (accessed August 22, 2005).

Note: 2005 figure was for the first six months of the year. Whitesides was a co-inventor on 68 patents. As of August 2005, Whitesides held no patents as a sole inventor.

Exhibit 15 Co-inventors on Patents

Whitesides held patents with 98 co-inventors from 16 U.S. states and seven other countries. On average, Whitesides' 68 patents listed 3.4 co-inventors in addition to Whitesides. Whitesides appeared as the first listed inventor 15 times and 43 times as the last listed inventor.



Source: Adapted from data from the U.S. Patent and Trademark Office, http://www.uspto.gov/patft/index.html, accessed August 22, 2005.