Anatomy of the Berkeley Sensor & Actuator Center (BSAC):

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Anatomy of the Berkeley Sensor & Actuator Center (BSAC):

The NSF Industry/University Cooperative Research Center on MEMS

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Abstract:

The Berkeley Sensor & Actuator Center at the University of California Berkeley has, for more than twenty-five years, had a major impact on the research foundations and consequent commercialization of MEMS and NEMS. This has been achieved through creative combinations of resources, incentives, and shared goals involving Academia, Industry, and Government. The strongly multidisciplinary and interdisciplinary operational model of BSAC (a National Science Foundation Industry/University Cooperative Research Center) is described.

Anatomy of the Berkeley Sensor & Actuator Center (BSAC):
The NSF Industry/University Cooperative Research Center on MEMS

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1. Introduction

The Berkeley Sensor & Actuator Center (BSAC) is the National Science Foundation Industry/University Cooperative Research Center on sensors & actuators and the only such center focused on Micro/Nano Electromechanical Systems (MEMS/NEMS). BSAC has over the past 25 years had a significant and persistent influence on Innovation Research in MEMS.

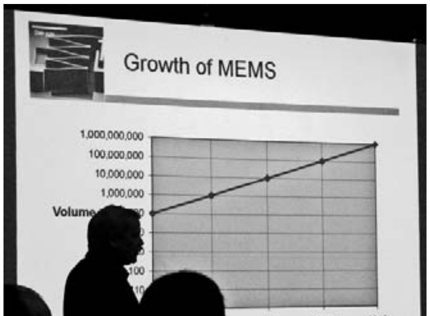


Figure 1: *Courtesy Richard M. White*

The center continuously evolves its operations model in order to effectively work with industry and government to help *transformations* into unforeseen *new* MEMS/NEMS technologies, products and markets. The model continues to catalyze innovation as MEMS/NEMS matures and as an industry based on these technologies awakes. This brief discusses the model and operations of the center.

2. The BSAC Legacy

A *sustainable research foundation* is essential to maintenance and growth of MEMS/NEMS- leveraged businesses and markets. This research foundation is the extended community of dedicated researchers practicing in public and private laboratories and managing research organizations worldwide. We publish in our own refereed journals and mingle at our own technical conferences and symposia.

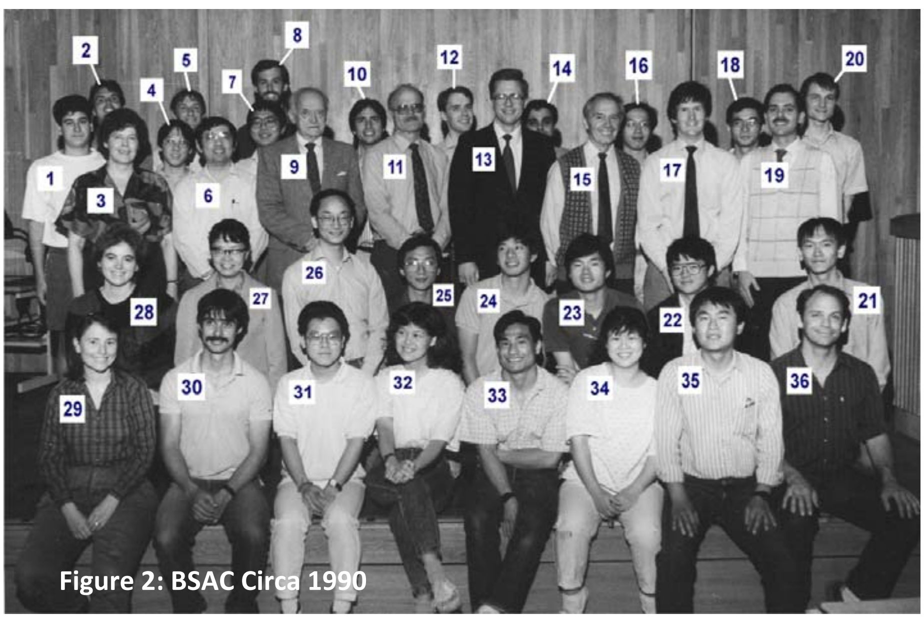


Figure 2: BSAC Circa 1990

The seeds of future MEMS/NEMS researchers are planted in our institutions of higher learning. The greatest contribution of BSAC to the emergence of these technologies has been in successive generations of graduates who have distinguished themselves in academic, industrial, and institutional organizations around the globe. Figure 2, just one snapshot of BSAC faculty and graduate students at one point in time, illustrates this contribution. BSAC Founders Richard Muller (11) and Dick White (15) and 2nd Generation co-Directors Albert Pisano (19) and Roger Howe (13) are pictured with 3rd generation BSAC co-Directors (here as graduate students) Liwei Lin (21) and Clark Nguyen (4). Not shown is future BSAC co-Director Kris Pister. Not all have returned to BSAC but most are well known researchers in the community, part of the "who's who" of MEMS. These and prior and subsequent classes of BSAC'ers have evolved into generations of creative practitioners spanning a large range of specializations and practices. The current roster of more than 150 future research leaders as well as a complete key to the photo and partial list of nearly 400 Alumni are on the

BSAC website (http://www-bsac.eecs.berkeley.edu/alumni/).   The current co-Directors of BSAC listed in Table I are consensus and emerging thought leaders, well known internationally; editors of refereed Journals of our industry, and frequent conference and workshop chairs, with very strong interdisciplinary credentials and orientation.

	Role		Department		Role		Department
Richard S. Muller	***Founding Director***	**1986**	**EECS**	**Luke P. Lee**	***co-Director***	**1999**	**BioE**
Richard M. White	***Founding Director***	**1986**	**EECS**	**Ming C. Wu**	***co-Director***	**2005**	**EECS**
Albert P. Pisano	***co-Director***	**1988**	**ME + EECS**	**David A. Horsley**	***co-Director***	**2005**	**MAE (UC Davis)**
Kristofer S.J. Pister	***co-Director***	**1996**	**EECS**	**Clark T.-C .Nguyen**	***co-Director***	**2007**	**EECS**
Bernhard E. Boser	***co-Director***	**1996**	**EECS**	**Ali Javey**	***co-Director***	**2008**	**EECS**
Dorian Liepmann	***co-Director***	**1998**	**BioE + ME**	**Michel Maharbiz**	***co-Director***	**2008**	**EECS**
Liwei Lin	***co-Director***	**1999**	**ME**				
(Former co-Directors: Roger T. Howe UC Berkeley/Stanford; Olav Solgaard UC Davis/ Stanford; Norman Tien UC Davis/ CWRU)							

Table I: Faculty co-Directors of BSAC (~Five Generations)

2.1 Goals of BSAC

(1) Create a leadership microsystems research environment. Combine the best researchers, faculty, and industrial partners. Bind them through the collective appeal of top rank University resources, an environment of collaboration, and access to a diverse group of Industrial members who are usually current or future market leaders in their segments.

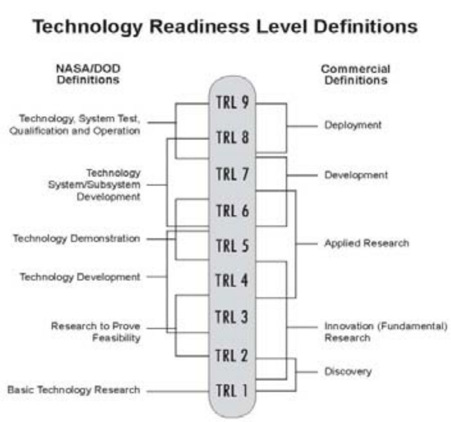
(2) Enhance the educational experience of our graduate students.

(3) Reduce the time to commercialization of BSAC research by Industrial Members and entrepreneurial researchers by establishing systematic progress in multiple phases of new technology formation: a)materials/process/packaging; b)devices and structures; and c)system integration. This strategy requires a broader range of projects and a larger research organization than most research consortia would be able to maintain.

(4) Maintain collaboration with Industrial Members to insure commercial relevancy of the research.

2.2 Research Readiness

Figure 3:



The BSAC model relies on reconciling University research *readiness* and *relevance* to the research-to-development cycles of our industrial members. Research within the MEMS/NEMS world ranges from short to long-term, with low to high risks and rewards, and with correspondingly varied funding and commercialization models, a continuum partitioned into broad domains with fuzzy boundaries: *Development*, *Applied Research*, *Innovation* (Fundamental) *Research*, and *Discovery Research*. Like U.S National Science & Space Administration (NASA) funding "Technology Readiness Levels" (TRLs), these research domains are simply a way to characterize technology maturity. (Figure 3).

Development is interpolative, with articulated product and market goals, funded with shorter term commercialization mandates, utilizing *existing* technologies and manufacturing. University research may have contributed some of the seeds and provided consulting and advisory services but this is the domain of industry. It is internally funded by and for existing industrial organizations or by new business entities externally funded by private or venture equity sources. It *capitalizes* on the upstream research domains.

Applied Research tends to an extrapolative or evolutionary nature, primarily funded by industry and/or government with somewhat longer term, higher risk commercialization as the primary goal, utilizing a constrained arsenal of proven or near-commercial technologies and manufacturing. These activities refine and target and extend existing or emerging technologies into new capabilities and applications, with an articulated view of endpoints. Most applied research is conducted in Industry or through industry-funded, contracted, sometimes collaborative research at universities and public or private research institutions.

As used here, the concept of *Innovation Research* refers to fundamental research *with commercial or societal motives as opposed to articulated product goals*. Innovation research is pre-commercial and is practiced by alliance of the scientific and engineering communities in the public and private sectors. It is the domain of *needs-inspired* discovery. It is generally *discontinuous* and may be *boundary-spanning* in nature, perhaps initiated without specific endpoints identified, but with commercial or societal impact as the justification and the motive. With "industry" operating on thinner margins in global competitive markets that demand research pipeline efficiency for survival, fundamental *Innovation Research is increasingly the domain of university-based, government subsidized, industry-relevant collaborative research*.

The most upstream in the research continuum is *Discovery* (basic) *Research* that at least in the United States is now nearly the exclusive domain of government-funded university and federal laboratories. Although discoveries eventually contribute to multiple engines of innovation, the focus here excludes the role of Discovery Research.

A point to be made relative to research practiced in many major U.S. research Universities including the entire University of California system and BSAC, is that the federal *fundamental research exemption* from export administration requirements (EAR) or export controls is asserted. That allows BSAC research publication and disclosures to be shared with our international researchers and industrial members without export license. This exemption places *constraints* on limitations of research disclosure and publication and obligations on the University and researchers. Exempted Fundamental Research *must* be freely, rapidly, and publicly disclosed and *may not be withheld* nor unnecessarily delayed for any proprietary purpose other than for initiation of patent applications or for pre-publication review by publication referees. There is an approximate correspondence between this definition of fundamental research and the characteristics of Innovation Research as described above.

3. Corporate Models for Innovation Research

BSAC has evolved a sustained model of industry collaboration as evidenced by an international roster of member companies(Table II), including ten with a decade or more in the Center, and five with more than twenty years of BSAC membership. As will be mentioned, NSF has the foresight to subsidize membership for small SBIR- funded companies who in some *cases may represent the fastest way to commercialization*. Before describing the BSAC model, it is useful to discuss the context of common corporate research models.

TABLE II

BSAC Industrial Members of Record (Period 2010-2011)		
**Analog Devices*	*Intel*	**Sandia National Laboratories*
Applied Materials	*Invensense*	**Siemens*
Bosch	*IRIS AO*	*Panasonic*
British Petroleum	*JetPropulsionLab*	*Phasics (SBIR)*
Capella Microsystems	*Lockheed Martin*	*Qualcomm*
Chevron	*Marvell*	*Raytheon*
**Draper Labs*	*Medipacs (SBIR)*	*Samsung*
Eastman Kodak	*Medtronic*	*Sharp*
FormFactor	*Mitsumi*	*Starkey Laboratories*
Freescale	*National Semiconductor*	*SVTC*
Fuji Electric	*NDK*	*Toshiba*
Fujitsu	*NGK Sparkplugs*	*Toyota*
Honda	*Northrop Grumman*	*TSMC*
**Honeywell*	*ON Semiconductor*	*Yamatake/Azbil*

** 20+ year BSAC Membership as of Fall 2011*

Corporations normally internally fund *advanced development* and Applied Research that is justified by specific, articulated business goals. Managed investment with expectation of positive research payback requires defined- scope projects. Financial measures, primarily ROI (return on investment) are often committed in the initial project proposals which also have "checkpoint" milestones that are measured and judged periodically as a condition for continued funding. Some higher risk internal research projects with less tangible outcomes may be justified in part by strategic impact on existing businesses and technologies.

This type "near-field extrapolative" Applied Research is essential to predictive and proprietary high-value product or process rollouts. It is NOT primarily justified on the likelihood of broader reaching, unanticipated, or breakthrough opportunities that might emerge from somewhat less constrained Innovation Research.

To address higher risk, high payback breakthrough efforts, large Corporations (with extensive research budgets) and profitable midsize, highly technology-leveraged companies may conduct earlier stage, less directed internal Innovation Research through *central* or *corporate funds* that have somewhat longer time frames and less quantified expectations for payback than do individual business units. But the number of such projects fundable from internal resources is necessarily limited, so significant pre-selection of projects is still required. Game-changing but poorly understood or higher risk options or promising approaches without strong internal champions may not be funded, with potentially huge lost opportunities for the corporation, or even survival risk from more aggressive competitors.

Another path to Innovation Research may involve collaboration with outside researchers who may not have the same predispositions, biases, or blind spots that internal corporate cultures may unwittingly create. Internal research groups may however resist or resent the consequent sharing of research funds or the implication that outside knowledge infusion is needed.

In order to encourage such collaborations, some corporations provide internal business unit incentives. Divisional or business unit research budgets are enhanced with corporate matching funds for business unit-defined and directed contracts with public or private research entities, in particular research universities. The resulting research projects benefit from infusion of fresh thinking while reducing the research costs and insuring some relevance to business unit commercial goals.

4. The National Science Foundation I/UCRC research model

BSAC has operated nearly from its inception in the mid-1980's as a U.S. National Science Foundation Industry/University Cooperative Research Center. This innovative federal program championed for 30 years by NSF Program Manager Dr. Alexander Schwarzkopf and in 2008 assumed by Dr. Rathindra DasGupta, sets benchmarks[1] in efficiency (ratio of total Center research budgets to federal program investment) and commercial relevance (ratio of industry funds to federal program investment) unmatched by any other U.S. federal research program of which we are aware. The NSF provides modest "startup funds" on a renewable five-year basis to University-based researchers who wish to combine efforts with Industry in a formal Center structure to conduct *commercially relevant* boundary-spanning research in a coherent subject area. The NSF I/UCRC centers have chartered research concentrations based on technologies (e.g. *Center for Biocatalysis and Bioprocessing of Macromolecules*) or applications (e.g. *Minimally Invasive Medical Technologies Center*).

The number of active NSF I/UCRC Centers typically ranges between 35and 50, with nearly 100 University "Sites" (Centers generally encompass multiple university sites). As Centers become self sufficient and "graduate", new Centers form. Each site is generally responsible for recruiting its own Industry Members, though BSAC treats all memberships as members-in-common for the two BSAC sites.

BSAC has, since 1986 been the NSF I/UCRC Center for sensors and actuators, the only one specializing in MEMS/NEMS. We added the University of California Davis in 1998 to the UC Berkeley center to become a two-site I/UCRC. BSAC is among the largest of (currently) 55 U.S. Centers in most significant categories: research budget, industrial member funding, and number of researchers. See Table II below and reference (footnote) 1. BSAC became a self-sufficient "Graduated" I/UCRC Center in 2009, and since March 2011, has operated as a Phase III NSF I/UCRC (NSF Program Solicitation 09-065). [2]

[1] NSF I/UCRC Program Evaluation Website, http://www.ncsu.edu/iucrc/
[2] Denis O. Gray & S.George Walters *Managing the Industry/University Cooperative Research Center*, Battelle Press, 1998

Table III: NSF I/UCRC Center Statistics		
Category	NSF Centers Average Jan 2010*	BSAC 2010-2011**
Faculty	14	13
Administrative Staff (w/ Director)	2.3	3
Technical Staff	3	1
PostDoctoral Researchers	4	36
Graduate Student Researchers	31	106
Undergraduate Researchers		13
Total Researchers	49	155
Industrial Member Organizations	21	42
Reported Research Projects	NA	124
Research Budget Total (000's)	$2,400	$14,900
Membership Fees Total (000's)	$700	$1,569
Membership Funding (w/gifts & sponsored research)		$4,355
Source: D.O. Gray & L. McGowen, North Carolina State University		
**NSF I/UCRC Center Directors' Report (see http://www.ncsu.edu/iucrc)*		
***Members of Record During the Period; Financials as of September 2011*		

Mandatory elements of an NSF I/UCRC include a formal *Membership Agreement*; *semiannual meetings* attended by all center researchers and industrial members, at which all center research is presented and *voted on* by industry members; an *Industrial Advisory Board* meeting at which center operations and management topics are discussed, including a closed *member-only executive session* with *formal paid NSF Evaluator* but without Center faculty present, at which center research and operations may be discussed and membership votes on center proposals may be conducted. Formal annual reports by the Center Director and by the NSF Evaluator to the NSF are required as are semiannual reports by the Center Director to the membership and faculty co-Directors.

The Center Director and NSF Evaluator attend annual NSF meetings of all Centers Directors and NSF program management to share experiences, challenges, and creative solutions relating to center operation and to industrial collaborations and to multi-site issues and University-Industry or Industry-Industry conflicts or tensions that can emerge. NSF Evaluators meet in common with NSF program management separately once a year to review program performance and issues.

These program elements in themselves, while part of a systematic management structure, may seem unremarkable. But the relatively open sharing of experiences, successes, conflicts, and solutions among all stakeholders in the I/UCRC centers: researchers, Center Director, staff and faculty, Industrial Members, NSF Evaluators, and NSF program management can only be described as a *culture*, with the shared goal of center successes. Other federal programs have mandatory semiannual research reviews and annual program meetings, where often the primary incentive to participation is continued funding. Given the modest funding levels available from the NSF I/UCRC program, that isn't the attraction. A primary incentive to active participation in the program and meetings is this remarkable *culture of collaboration*, in which Universities are brought together in the multi-site arrangement, and in which technology practitioners and managers from multiple, sometimes competitive industrial organizations sit together in review and support of important, hopefully "game-changing" industry-influenced pre-competitive research .

5. ***BSAC Research Model and Experience***

The BSAC research model and its rationale and implications might now be understood in this context of the corporate research environment and the NSF I/UCRC program under which it has operated successfully for nearly 25 years.

5.1 BSAC Mission Statement: *This Industry/University Cooperative Research Center, founded in 1986 as the National Science Foundation Center for Microsensors and Microactuators, is devoted to commercially relevant interdisciplinary engineering research on micro- and nano-scale sensors, moving mechanical elements, microfluidics, materials, processes, and microsystems that take advantage of progress made in integrated-circuit, bio, and polymer technologies.*

BSAC Participation Agreement Excerpt: Membership Benefits

a. Each Industrial Member will receive all new and electronically archived BSAC publications, including theses and papers appearing in peer reviewed literature, as they are published, either by electronic means, or upon request, via hardcopy or physical electronic storage media.

b. Attendance at semi-annual research review meetings held at the UC Berkeley campus to review, assess, critique, and advise on recent, not yet published or publishable, research results.

c. Opportunity to influence the research topics of BSAC through representation on the Industrial Advisory Board (IAB).

d. Invitation to meetings of California's College of Engineering Industrial Liaison Program.

e. The right to use, subject to California's valid copyright and patent rights, all reports, data, and information made available by BSAC, so long as BSAC is acknowledged as the source of this information, and Prepublication Data is protected according to the prepublication nondisclosure agreement.

f. Access (nonexclusive license) to intellectual property developed by BSAC in the course of research funded by the membership fees of Industrial Members, on terms as provided in the membership agreement.

g. Early (90-day) access to inventions developed from BSAC research programs that were funded solely by agencies of the Federal government or the State of California.

h. To the extent permitted by funding agencies, the right to propose and participate in joint research programs, with BSAC Directors, funded by agencies of the U.S. Government.

i. The opportunity to sponsor and fund separate projects with BSAC Directors after mutual agreement. Any joint or collaborative research conducted between the parties shall be defined and governed by such separate Sponsored Project Agreements. Intellectual property rights to inventions arising under such sponsorship will be defined by such separate agreement.

j. The opportunity to send, with separate agreement and fees, for periods ranging up to 3 years, a Visiting Industrial Fellow to BSAC for in-residence research, sponsored and advised by a specific BSAC co-Director who acts as campus host.

l. Guaranteed eligibility to membership in the Berkeley Microfabrication Laboratory Affiliates (BMLA) program to access the Marvell Nanofabrication facility, under separate agreement, with additional fees and under terms more favorable than offered to non-BSAC members.

5.2 Intellectual Property : One of the considerations and concerns confronting industrial participation in a research consortium involves the treatment of inventions and intellectual property. For purposes of early disclosure of unpublished research, the membership group in this model constitutes an extended research review committee or board, and the disclosures at our semiannual review are not considered public disclosures. So that researchers can do this without loss of subsequent publication rights or occasionally, patenting opportunities , the BSAC membership agreement contains a simple "prepublication nondisclosure agreement" to preserve these rights for the researchers for a very limited period following first membership disclosure at one of our closed semiannual membership meetings.

The BSAC IP policy is to *implement the IP policies of the University of California to the advantage of our membership and researchers*. The U.S. Bayh-Dole Act of 1980[3] essentially gives custodial and licensing rights to the University for inventions and patents that are created from federal funding, for the purpose of maximizing the generation of commercial activity and business formation. Previously such rights were the property of the federal government. The University of California policy is that University researchers generally have an obligation to report inventions. On the other hand, BSAC faculty also have both a freedom should they so elect, and even an obligation to publish early and often, the process of which may put results of their research into the public domain without patents.

The BSAC IP facilitation role is early (90 day advance) disclosure only to our members, of BSAC inventions, *should they occur*, and facilitation of access to UC Berkeley's office of Intellectual Property and Industry Research Alliances (IPIRA), the office charged with management of all IP of the campus. This facilitation takes the form of an automated BSAC disclosure management system linked to the IPIRA office whereby BSAC members can receive invention notification abstracts within hours of their release, and can receive detailed disclosures with one-click requests to IPIRA. The policy of the US Department of Commerce is to allow and in fact encourage collaborations between industrial and academic researchers by creating a "safe harbor" for such collaborations. However to avoid unconstrained internal disclosures and possible contamination of not yet public invention information, BSAC implements "gatekeeper" protections for member companies who do not want detailed invention disclosures automatically sent to their employees. For those companies, BSAC automatically routes member requests for detailed invention disclosures to the company Gatekeeper who can with one click authorize or deny the request.

If researchers do decide to submit invention disclosures, it is important that they do this quickly so that Industrial Members are advised quickly of prospective patent applications. BSAC insures timely submissions by effectively disclosing, through public "recording", ALL our prepublication data not more than 12 months following the IAB review at which first disclosure occurs. This "recording" constitutes a public disclosure, whether or not individual results have been separately published, hence putting a time limit on subsequent patent applications. This early and broad public disclosure and recording also serves to satisfy a requirement for maintenance of our *fundamental research exemptions* from export license requirements (EAR and ITAR).

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[3] "The Bayh-Dole Act:A Guide To The Law And Implementing Regulations" http://www.ucop.edu/ott/faculty/bayh.html

Furthermore, while the center administration does facilitate notifications of inventions and access to licensing officers, they do not get involved in discussions or negotiations between Industrial Members and the licensing officers on matters related to specific IP licensing. BSAC administration generally is not even informed as to when or with whom licensing discussions may be underway so as not to compromise the interests of industrial members, the University, or the researcher(s)/inventor(s).

5.3 Boundary-spanning

The technologies of MEMS and NEMS are by nature strongly interdisciplinary, dependent on *integrative* approaches from disciplines that may include mechanics, electronics, materials science, chemistry, microfabrication, biology, physics, clinical research, public health and others. It is hard to imagine organizations other than world-class research Universities or research institutions that contain quality researchers from these disciplines *sufficient* to create “game-changing” research breakthroughs.

However *within* the University structure where disciplinary walls may be very high, combining researchers into effective *problem-oriented teams* more typical of industry and required for extreme interdisciplinary progress, can be difficult. Departmental criteria for tenure and promotion may not reward such teaming.

BSAC was arguably the first declared multidisciplinary problem-oriented Center within the College of Engineering at UC Berkeley . The formal, NSF-chartered organizational structure of the I/UCRC may have helped validate the interdepartmental faculty affiliations & disciplinary boundary spanning necessary for a MEMS Center. Admittedly our founders Muller and White were both from Electrical Engineering; it wasn’t until Albert Pisano joined the founders as co-Director from Mechanical Engineering that the departmental boundaries were first challenged. BSAC has over the years had success bridging these departmental bounds in part because our faculty co-Directors have included the department or division *chairs* from Mechanical Engineering, Electrical Engineering, and BioEngineering at UC Berkeley, and Electrical and Computer Engineering at our UC Davis site. And over the past twenty-five years, U.S. research universities and institutions have adopted to the necessity of discipline-spanning to address both commercial and societal problems (and funding opportunities) that cannot be contained by departmental boundaries.

The word has been heard: “Ms. Chairman, tear down these walls”.

Today, BSAC has in addition to 13 permanent faculty co-Directors from 4 departments on 2 campuses , semiformal (co-advising) arrangements for research project collaborations with faculty from other departments that from time to time include Molecular & Cell Biology, Computer Science, Chemical Engineering, Civil Engineering, Chemistry, Physics, and other institutions and campuses such as Children’s Hospital Oakland Research Institute (CHORI), and UC San Francisco. Interdisciplinary interdepartmental cohabitation within University-based centers is becoming a U.S. research university norm rather than an aberration.

5.4 Linkage Mechanisms: The concept of "*Industry/University linkage mechanisms* that allow universities and industry to meet each other half-way, at their organizational periphery…and which link dissimilar institutions and buffer conflicts or friction" has been studied extensively over many years, and is effectively described in the context of the I/UCRC program by Prof. Denis Gray, organizational psychologist from North Carolina State University [4]. The I/UCRC is one such mechanism. Within the I/UCRC model there are a number of specific structures , incentives, and transactions that address unifying the disparate profit/market goals of industry and discovery/ knowledge sharing of universities.

Figure 4: BSAC Commercialization Symposium

5.5 Commercial Relevance: Above all, Innovation Research practiced in the University-based centers, while "pre-competitive", must show at least the *prospect* of some future commercial benefit to justify and reinforce industrial participation. Commercial relevance must be continually in view of member organizations in order for their participating champions to rationalize the external use of (scarce) corporate or institutional research funds. BSAC-sponsored sessions at our semiannual reviews such as illustrated by the cover of a BSAC Symposia Proceedings in Figure 4, attempt to reinforce the connections between upstream research and downstream commercialization. The symposium agenda is worth elaboration here because it illustrates multiple linkage elements that bridge the I/U divide. The agenda included specific references to *research readiness assessments* and to *multiple commercialization paths* for candidate university research projects:

1) **Research Internalization** to the benefit of corporate products/projects as illustrated by a keynote address from Dr. Gilbert Hawkins, Eastman Kodak Associate Director of Research (retired) who described in detail a multi-year Kodak project to build a high speed high resolution digital offset printer. Kodak has been a long term industrial member with interests in Microfluidics (one of eight BSAC technology thrusts). The contributions of BSAC research to the project were through Dr. Hawkins' long term proactive engagement with faculty and graduate student researchers rather than through specific sponsored research. This might be thought of as *mutual enlightenment* through the frequent, in-depth collaboration opportunities provided by Center reviews and activities. The benefits are mutual because of the motivational and intellectual benefits to student researchers through contact with and insights of expert industrial members .

[4] Denis O. Gray in *Managing the Industry/University Cooperative Research Center*, (Ed: Denis Gray & S.George Walters) Battelle Press, 1998 p 5-8

2) **The maturation of specific university research** as reported by three BSAC faculty co-Directors each of whom picked one of their current research projects that they proposed as both relevant and ready for initiation to the long and tortuous road toward commercialization.

3) **New business formations** based on prior BSAC research projects, by four graduated BSAC PhD researchers who were at the time of the Symposium, in various phases of taking their dissertation topics to commercial products.

4) **Readiness and relevance assessments** of the previously described projects by a panel expert in MEMS markets, entrepreneurial MEM start-ups, university incubator, and Venture funding.

6. Influencing Research Directions (Incentives and Leverage)

In the NSF I/UCRC model as most commonly practiced, this commercial relevance is assured by "democratic" project selection. Researchers submit project proposals to the Industrial Advisory Boards comprised of industrial members who actually "vote" on research projects to be conducted and funded from membership funds. The incentive to clear commercial relevance is therefore high. But the risk factors in such research topic selection may be correspondingly low to the point that the projects may be downstream (toward commercialization) even from applied research and may be almost in the category of advanced development. The likelihood of fundamental breakthroughs and unforeseen benefits may be proportionately diminished by low risk and low-to-moderate rewards. If the "technology readiness" is too high, the projects so selected may be past the "pre-competitive" phase in which multiple industrial participants can jointly support the research with expectations of differentiated benefits from its application.

Within BSAC and many I/UCRC's, the tendency is to more upstream research with higher risks, and longer "gestation" to direct commercial application. The BSAC Industrial Advisory Board has taken positions favoring upstream research. But without some process or incentive toward commercial relevance, industrial participation would over time diminish, and Industry/University common purpose would be at risk. Some balance is required. To that end, we use a novel process for incentivizing balance among research creativity, risk, relevance, and readiness.

6. 1 Research Area (vs Project) Targeting: Our fee-based membership organization uses member fees to focus our research into commercially relevant areas. These funds also support the common infrastructure of BSAC: outreach events, semiannual research reviews and IAB meetings, visitations and regional research reviews in Europe and Asia; administration (invoicing, contracts, publications and pre-publication distributions), facility and common equipment investments, and some microfabrication process development. Member fees net of these operations costs are distributed not to specific projects as is the case in most National Science Foundation I/UCRC's but rather to individual faculty co-Directors who tend to specialize in specific MEMS/NEMS research areas.

6.2 Unknown Breakthroughs: The BSAC IAB authorized to award up to 50% of their net fees *uniformly* to all active faculty co-Directors because of their perception that *if they knew exactly where the big payoffs in upstream research were, they wouldn't need to" hedge their bets" in external research consortia such as BSAC*. In short, they express confidence in the overall research agenda of BSAC and the possibiity that breakthroughs might well come from unanticipated areas and researchers. This is a strong testimonial to their commitment to upstream, Innovation Research.

However members *do target at least half of their net membership fees* to specific faculty co-Directors based upon an annual vote in which members distribute their fees over any combination of faculty co-Directors whose research they favor: all to one, 50%-30%-20% to three, etc. And faculty respond. This reward system is a subtle but critical determinant of success for the center. Without some discretionary directing of membership research funds to faculty, the faculty motives to routine industrial collaboration and support would be diminished. Faculty have a lot of "mouths to feed" in terms of securing continuing funding for their graduate students. But unlike contracts with strict spending constraints and prohibitions, membership fees are the most unrestricted of research funds, and therefore the most valuable, useable for all allowable University purposes, including international collaborations, summer salaries, and seed funding for new ideas and proposal generation.

6.3 Membership Recruitment & Nurturing

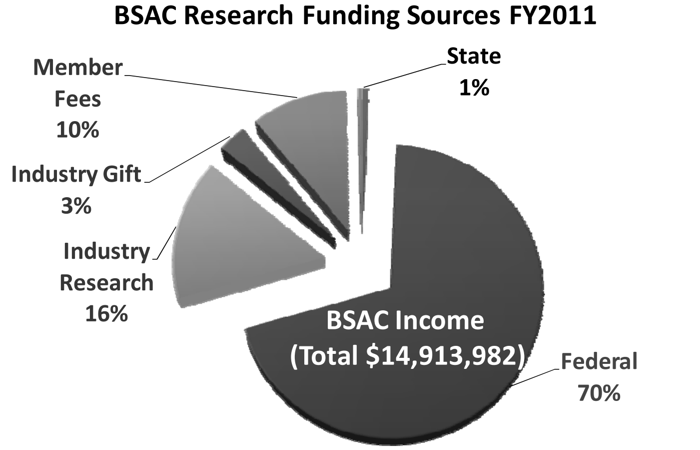
For the first year, new members are able to designate all their membership fees (net ofoperations costs) to the faculty responsible for ther membership. This encourages recruitment and early coupling between faculty and industry.

6.4 Industry (Sponsored) Research

When (and if) commonly supported research leads to opportunities for more directed but still pre-commercial efforts, members have the option of proposed engagement with specific faculty on "sponsored research" contracts in which industrial members may negotiate research elements and IP (patent) provisions favorable to their interests within the agenda of the faculty and consistent with dissertation requirements of graduate student researchers who may be primarily conducting the sponsored research. BSAC faculty co-Directors in fact will engage in sponsored research only with Industrial Members. All results of such sponsored research are publishable by the researchers without limitation, but the close engagement and collaboration of sponsoring Industrial Member with the researchers in negotiation and continuous, proactive review of the research, yields significant advantages to the sponsoring members, and consequent validation of the I/U linkage processes.

7. Research Leverage

Figure 5
BSAC Research Funding Sources FY2011



One of the great value propositions for University-based Industry/University research centers can be the "leverage" or "amplification" of member fees, that expose industry to far more research than could ever be funded by the relatively limited center industrial fee structures. For example, the membership fees from our (approximately) 40-member organization accounts for less than 15% of BSAC total research budget (Figure 5).

But total *membership-related* research funds are enhanced by industry gifts and sponsored research, representing a large amplification of membership fees. The bulk (70%) of BSAC research funding arises from competitive external awards, typically from the Defense Advanced Projects Agency (DARPA), NSF, National Institute of Health, Army Research Lab, the California Energy Commission, US Department of Energy and other federal agencies.

Although many research centers including many I/UCRC's may not operate in this way, all BSAC faculty co-Directors and all their graduate student and postdoctoral researchers report on *all their research* to BSAC member companies on a prepublication basis every six months (without regard to whether results have been yet submitted for journal or conference publication or patent protections; see the sidebar on "Intellectual Property"). Members receive early access to invention disclosures (if any) for all center research, not just the 20% enabled by membership fees.

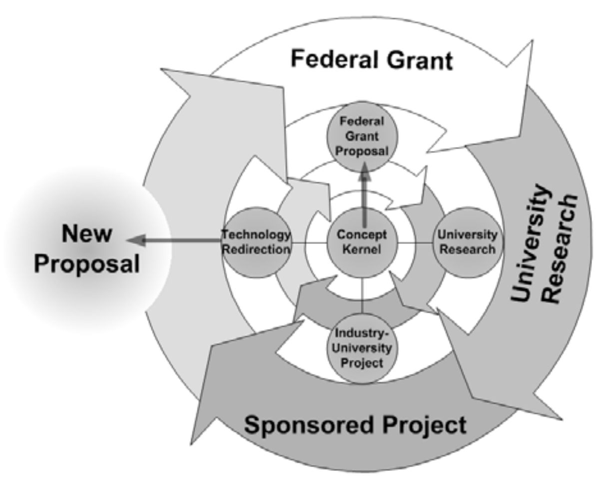
By formal agreement, our co-Directors reserve their industrial collaboration "bandwidth" for our industry members (see "Membership Benefits"). Specifically they engage in Industry Sponsored Research with, and host Visiting Industrial Fellows only for industry members.

Furthermore, only our industrial members have the option of collaboration and co-authorship of joint industry-university proposals for external (usually federal) competitive awards or contracts in which the BSAC faculty is the "lead" and in which industry is *recipient* of research funds.

7.1 Federal Research Synergies :

Professor and BSAC co-Director Albert P. Pisano argues that federal and industry funding become linked through creative synergistic processes unleashed in the I/U environment, as illustrated (Figure 6). Seed-funded research from limited industrial funds generate a concept kernel that leads to a federal proposal and competitive grant that funds higher levels of University research that an ndustrial member leverages in an industry sponsored project, leading to new idea formation and redirection in the center to a new competitive proposal, *ad infinitum*.

Figure 6: Federal-University-Industry Research/Funding "Helix"



These are subtle but powerful processes in which one has to participate to fully understand. The role of the industry participants to add the criterion of potential commercial relevance to feed and sustain the cycle ("knowledge creating wealth") distinguishes it from other pure academic-government research agendas ("wealth creating knowledge") that may lead to inversion of cause and effect.

The concept of *research syndication* flows naturally from this model in which modest membership fees are amplified by external research funding and by creative, collaborative minds to create a large research effort from what amounts to industry "seed funds".

7.2 Research Funnels and Seed Farms:

One "rule of thumb" used by some venture analysts and corporate planning committees is that the cost of research/advanced development is only 10% of the overall product development-to- launch cost (if new manufacturing processes or new markets are implied, the ratio will be much higher). All eleven Federal research agencies (DARPA, DOE, NIH, NASA, DOC, etc) set aside some of their operating budgets to fund promising Innovation Research through an SBIR* (Small Business Innovation Research) program in two phases: Phase I to allow basic proof of concept demonstration, and Phase II to take the most promising survivors of Phase I through development to initial commercialization. The Small Business Administration (SBA) of the Department of Commerce recently revised funding levels upward to $1,000K Phase II/ $150K Phase I (from prior $750K Phase II/$100K Phase I). No SBIR funds can be used for marketing, so when modest marketing costs are added to Phase II, a ratio of 10:1 or higher emerges. These ratios illustrate the criticality of corporations to reduce a large population of candidate projects to the *chosen few* early in the innovation process. The I/UCRC program does just that.

Figure 7
BSAC Research (Agenda Categories)

"Microtechnology"	*Projects*
Process, Packaging, Microassembly	6
Physical Sensors, Actuators & Devices	29
Wireless, RF, & Smart Dust	14
MicroPower/Energy Scavenging	10
subtotal	*59*

"NanoBioPhotonics"	*Projects*
BioMEMS	17
Microfluidics	16
Nanoplasmonics, µPhotonics & Imaging	13
Nanotechology:Process, Materials, Device	19
subtotal	65
Total Projects	**124**

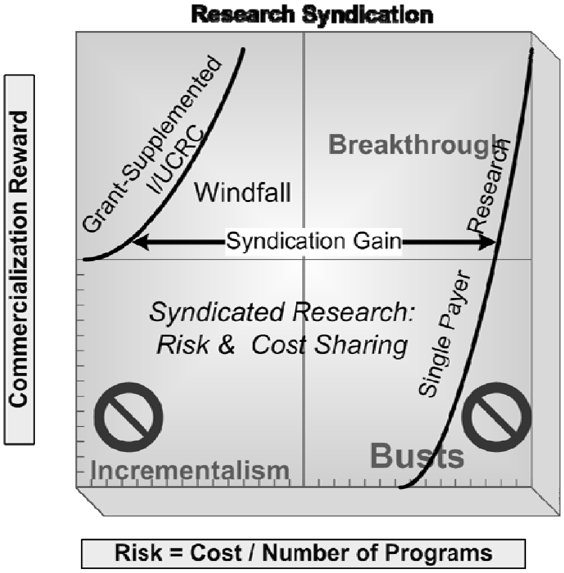
The classic model of a "development funnel" is familiar: a relatively large number of product, market or development ideas and proposals are offered (mouth of the funnel), in a *limited resource environment* (diminishing volume) and a *selection process* successively eliminates candidates according to some criterion until surviving projects (exiting the apex of the funnel) become fully funded. The model assumes that as the projects are allowed to progress, that more resources are applied, until the most worthy emerge fully funded and suitable (with subsequent investment) to realize business objectives . The 124 recent BSAC projects from eight research categories contain a lot of ideas (figure 7).

Funnels are cold mechanical structures without an organic context, so the *seed farm* is perhaps a better way of visualizing the process. The concept of "seed funds" has in fact been suggested to characterize the industrial investment. Many seeds are in the soil, and some will germinate but only those that receive the *correct* nurturing combination of nutrients, light, water, and temperature will thrive. But the sustaining environment for a cactus will not sustain a water lily. One interesting thing about a research consortium like BSAC is that we have 40 somewhat distinct environments, each correct for some species or varietal. We need an initial population of generally healthy seeds, resources to germinate and a selection process whereby the most worthy surviving plants will be adopted by the sustaining environment (company) in which it can thrive to a bountiful harvest.

7.3 Research Syndication

Figure 8 illustrates conceptually some of the benefits of precompetitive/precommercial research syndication. A goal *of fundamental research is avoidance of incrementalism* or incremental product enhancements*.* Unless the enhancements involve breakthroughs in some underlying process, component or material, they are best done in the internal development environments of the corporations. Research is about seeking breakthroughs, "game changing" materials, processes, devices, and methods that fundamentally change the dynamic for the targeted markets. *Bandwagons don't win races*.

Figure 8
Research Syndication



"Single Payer" breakthroughs (implemented entirely inside the corporation) require a large investment and great execution on a superior idea; a large wager on a single number at the roulette wheel.

The advantage sought through syndication is breakthrough results with lower investments, a "Windfall", an unanticipated return on investment. That is where the leverage of a well-conceived and well operated I/U consortium can pay huge dividends. It is a way of potentially and dramatically *lowering the R&D costs of fundamental Innovation Research*.

By sharing costs of *precompetitive* research with a group of investors, many more ideas can be offered than could be funded in the single payer model where each industrial member completely funds exactly the project(s) of probable initial interest. In fact the gain is 40 for a 40-member consortium. But in a consortium in which 70% of the costs are borne by non-member related funds, and in which all benefits of the total investment are given to the member group, there is another 3.3:1 leverage or gain. Each member can effectively evaluate 133 times the number of embryonic projects as they would be able to fund from their individual membership investment (Figure 9). As previously discussed, *early* evaluation of promising projects and reduction of development candidates before launch of real development is the goal- and the benefit of such pre-competitive syndication.

Figure 9: Syndication Gain:

40 members
70% of Research Costs Borne by Competitive Awards
=133:1 Research Cost Leverage

Committed and Talented Researchers: BSAC has approximately 155 researchers reporting on 124 research projects, each of which represents the *passion and total commitment* of (usually) *one PhD researcher who individually has their dissertation relying on that project*. In effect each member has these 155 carefully selected "warriors" working on 124 projects at an annual cost per member less than the cost of supporting a single PhD student for one year.

That point should be reinforced by members looking to justify their participation, because quantifications of "measurement of success" are very difficult to defend.

8. Outcomes

8.1 Measuring Success

Return on investment of R&D is notoriously difficult to quantify even after the fact, when the research and development is "complete". But research advocates will be held to some indicators of success.

Though corporate cost accounting is a highly evolved discipline, there are fuzzy boundaries between research-to-commercialization phases; and (re)development may continue well into the commercialization phase. The research costs of I/UCRC participation while very easy to track, is, in the scope of a complete development program, quite small. What is more important and more difficult to track is the "return" for each dollar of research investment. Many research projects "contribute" to a commercialization but may not represent all or even the dominant portion. Even highly subjective things like *impact on brand valuations*, *pull on other products/businesses*, and *opportunity costs* may be part of corporate return on investment.

The I/UCRC "champion" within the corporation may therefore have problems assessing outcomes of I/UCRC participation and selling the benefit of such participation to senior technology and corporate management. There are real challenges even identifying *whether and how* the I/UCRC has contributed to internal research and development (and especially to subsequent products or processes).

Internalization of I/UCRC research results are difficult to document. Large industrial members generally do not advertise the contributions of outsourced (i.e. I/UCRC) research to their products or businesses, especially if those contributions relate to mainline businesses or core competencies. So the I/UCRC may not have verifiable and almost certainly not quantified data relating to the "value of membership".

Continued participation over many years by industrial members, (ten with more than a decade in BSAC and four with more than twenty years) while indicators, do not quantify the value of membership.

Very recent (unreleased) studies undertaken by the NSF in 2011 and based on interviews with multiple industrial I/UCRC partners have quantified BSAC commercialization returns at a very large ratio compared to total investment. Until these studies are audited and approved for release, specifics cannot be cited or disclosed. But even beyond the high direct dollarized returns, all participants indicate "acceleration of internal R&D" as major benefits of I/UCRC participation.

8.2 MEMS Industry Group

Any assessment of commercialization success must recognize the emergence over the past 25 years of what is now a multi-billion dollar high growth, high technology industry based on subject MEMS/NEMS technologies. The MEMS Industry Group (MIG) formed in 2001 to provide voice and an organization for common cause to an embryonic industry[5]. MIG has grown rapidly to a high vitality and high visibility organization with more than 100 member companies and organizations including 35 current or former BSAC I/UCRC member companies.

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[5] http://www.memsindustrygroup.org/

8.3 Indirect Benefits (Transitional Exposures)

Breakthrough inspirations may come not just from continued exposures to technologies directly in one's normal line of sight or area of specialization, but from *translational creativity*: exposures to unrelated or weakly related technologies. Some of the value of real-time, in-person I/UCRC participation is subjective "consciousness raising" associated with the "outreach" and incidental learning experienced by the industry participants at and between IAB meetings. Observing regular semiannual progress of 120+ projects creates a lot of "out of the box" thinking, since the scope of such a broad research agenda is necessarily beyond the specialties of any particular member.

8.4 Start-Up Linkages: Another measure of the success of I/UCRC research is the rate of generation and success of start-up businesses that trace themselves in some way to the center. This measure is particularly significant because a primary goal of some forms of federally-funded research is commercialization and economic development, particularly by small companies (Bayh-Dohl Act previously referenced). UC Berkeley in general and BSAC in particular, have traditions of business formation by our graduates. The BSAC website at last count listed 25 recent (most within ~6 years of launch) start-up companies who by their own estimation were "BSAC-inspired"[6] . These companies frequently license BSAC inventions through the campus Office of Technology Licensing. They often compete in (and often win) campus and national business plan competitions even while researchers are finishing their disserations and degree requirements. Of course not all these start-ups succeed, but the survival rate is surprisingly high. Most of the twenty-five BSAC-inspired startups either were still in operation or had been acquired in the six-year window of our first observations[5].

Whereas the commercialization of center research by the researchers themselves may at first consideration appear to be a "pre-emption" or diversion of technologies that were in part funded by industrial members, in fact the opposite is true: researcher entrepreneurial behaviors often work to the benefit of (large) member companies by risk reduction prior to industrial investments.

Early phase, emerging technologies are best understood by the (graduate student) researchers and faculty who developed them; and may be premature for importation into a large organization without a committed internal champion who can build a development team to finish the research phase and to marshall the project through internal competitions for subsequent funding. The best path to commercialization may therefore sometimes be by start-ups funded through competitive awards (such as Small Business Innovation Research SBIR) that allow graduated researchers to continue the project externally prior to venture funding or investment/acquisition by an industrial member company.

The NSF SBIR program management views the I/UCRC environment as a fertile one for connection of small SBIR companies to larger industrial members who may become investors, strategic partners, or customers. At the completion of a Phase II SBIR award and perhaps an Advanced Technology Program (ATP) award which can be an industry-led joint venture, the technology may be far more suitable for industry member adoption. A program of the NSF[7] specifically links the I/UCRC and SBIR programs by provision of a supplement to the Phase II SBIR awardees to join (for two years) an I/UCRC of their choice.

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[6] See http://www-bsac.eecs.berkeley.edu/startups/

[7] NSF09065 Supplemental Opportunity for SBIR/STTR Memberships in I/UCRCs

9. Some BSAC Research Results

Among the pioneering milestones, firsts, or significant benchmarks of BSAC are

- 1. First Surface Micromachining of Polysilicon
- 2. Thin-Film MEMS Poly-Si, Silicon Nitride, Silicon Carbide
- 3. Gyro Inertial Sensors and Accelerometers
- 4. Lamb Wave Acoustic Sensor
- 5. "Smart Dust" Wireless Sensor Network
- 6. Acoustic Wave and Fluidic Micropumps and Mixers
- 7. MEMS Micropositioning Components & Systems for Hard Disk Drive
- 8. Surface-Micromachined Gears, Cranks, Springs, and out-of-plane Structures.
- 9. Anti-Stiction Elements, Dimpled Structures, and Surface Treatments
- 10. X–and Y-Rastered Real-Time Projected Display System
- 11. Piezoelectric MEMS Silicon-Diaphragm Microphone
- 12. Localized thermal bonding for micropackaging and fluidic / biosample encapsulation
- 13. Precision controllable arrays of polymer lenses and mirrors for adaptive optics and imaging
- 14. MEMS Micro-Vibromotors
- 15. Comb-Driven MEMS Actuators

9.1 Surface Micromachining of Micro Electro Mechanical Systems (MEMS)

The basic idea of MEMS "surface micromachining of polysilicon" first perfected at the Berkeley Sensor & Actuator Center [8] in the work of BSAC cofounder Richard Muller and researcher Roger T. Howe, was to use small variations in standard CMOS microelectronic processing, to create *polysilicon* moving electro-mechanical structures (like clock pendulums on a microscale) that could exploit the incredible progress of the *Integrated Circuit* / *Microprocessor industry* and benefit from "Moore's Law" in which component complexity and value doubles every 24 months. About the same time, BSAC cofounder Dick White and researcher Jonathan Bernstein were developing Aluminum Nitride piezo thin film acoustic transducers in a CMOS-compatible technology[9].

Prior MEMS processes utilized "bulk micromachining", a silicon-based process that shares materials, chemistry and lithography with integrated circuit technologies but that has limitations integrating with the continuing "treadmill" of mainstream CMOS technologies. In contrast, MEMS utilizing *polysilicon surface micromachining*, put MEMS on a potential cost and complexity/ productivity path to mainstream CMOS memory and microprocessors. Bulk and surface micromachining still coexist and have both contributed to the commercial emergenc e of MEMS. But BSAC-catalyzed surface micromachining opened doors to new generations of MEMS devices that capitalized on the miracles of the integrated circuit industry.

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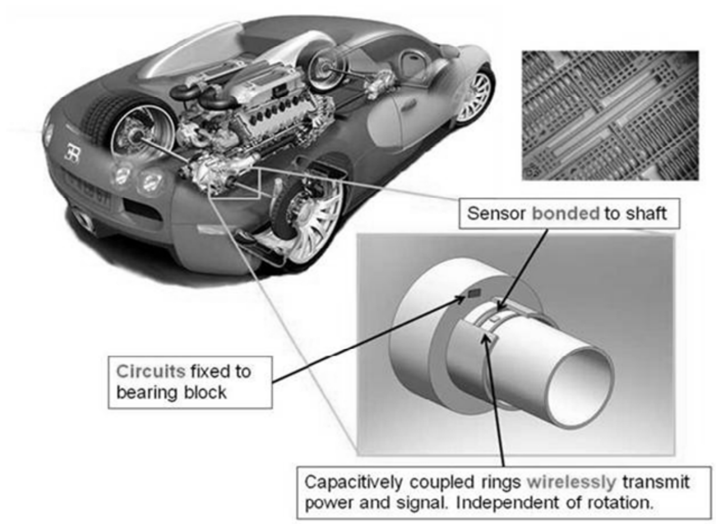
[8] R.T. Howe and R.S. Muller, "Integrated Silicon Microelectromechanical Vapor Sensor". Ph.D. Dissertation, May. 1984

[9] J.J. Bernstein and R.M. White, "Integrated-Circuit-Compatible Electret and Condenser Ultrasonic Transducers". Ph.D. Dissertation, Nov. 1983

Benefits deriving from resulting MEMS components are remarkable. Accelerometers utilized in automobile crash mitigation (airbag deployments) have been estimated to save more than 7,000 lives per year in the U.S. alone (Figure 11). Implantable inertial sensors are now used for early detection of heart pre-failure conditions, in time for interventions. Accelerometers used in wireless pedometers encourage measurement-based health and fitness applications. Accelerometer and Gyroscope-based navigational devices being introduced in cellphones hold promise for sensory-impaired persons.

Figure 11: MEMS Strain Gauge & Accelerometer for Vehicle Stability Control

(Courtesy Berkeley Micromechanical Analysis & Design Lab)



This pioneering work on polysilicon surface micromachining set in motion an escalating series of inventions by BSAC and others that changed not just implementations of, but fundamental concepts of where motion and inertial sensing and detection might be employed.

Fast-forward two decades from the original work and you now find MEMS accelerometers and related components in giga-volume quantities in industrial, medical, and consumer products ranging from previously mentioned heart motion monitors to vehicular stabilization systems to camera image stabilization to building, bridge, and pipeline structural health monitoring to location sensors and "air navigation" devices in cellular phones and gaming products. Application-based small (niche) businesses and service-based businesses can be spurred by broad availability of low cost transformational devices (such as inertial sensors). Witness the growth of niche businesses based on embedded firmware enabled by single board computers which in turn resulted from the single –chip microprocessor introduction in the 1970's.

These "microelectronic inertial sensor" applications have grown into an international multibillion dollar product category that creates even higher value in the products and systems in which they are employed.

9.2 Smart Dust

Located in Fremont California, Dust Networks is a privately held venture-funded company focused on providing wireless sensor network products to industrial and commercial markets. Dust Networks was founded in late 2002 by a team led by Kris Pister, a professor at the University of California, Berkeley, co-Director of the NSF (National Science Foundation) Berkeley Sensor & Actuator Center (BSAC), and the originator of the Smart Dust concept[10] (Figure 12). Industrial seed funds in 1997 (from Hughes Corp) along with small California state matching funds and collaboration with BSAC PhD candidate Joe Kahn and Computer Science Professor Randy Katz, were enough to launch initial experiments that would prove to be catalysts for a groundswell of academic and eventually federal and commercial investments.

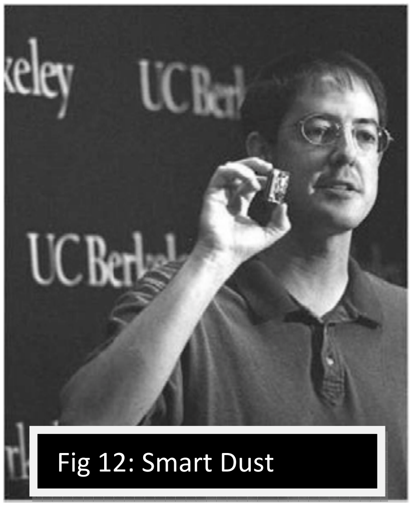


Fig 12: Smart Dust

DARPA provided additional project funding, and the resulting commercial venture years later is an example of university research becoming an economy driver from the efforts and commitment of entrepreneurial researchers. Pister extended the DARPA project results and championed his “Smart Dust” concept (networks of communicating wireless sensors) within the research community at UC Berkeley[11].

He collaborated with Prof. David Culler of the UC Berkeley Computer Science Division who launched an open source initiative for creation of the first systematic wireless sensor *network operating system* called *TinyOS*. A real-time demo of 800 self- configuring wireless sensors in a self-healing network at BSAC Industrial Member Intel Corporation’s developers’ conference helped to bring the proof-of-concept technology to a pre-commercial phase.

In January 2003, Prof. Pister took industrial leave from UC Berkeley and BSAC and, with former students and collaborators, formed Dust Networks. Since then, the company has raised $31M in venture partner funds. Dust Networks subsequently developed a unique patent-pending networking system that addresses the needs of a broad range of customers who need an enterprise-class, wireless mesh network and system for sensing and control applications.

Their flagship effort –the SmartMesh™ networking system facilitates the deployment of sensing and control solutions, and provides access to information about the physical world; information that will be used to increase occupant comfort in buildings, to reduce energy consumption, to reduce machine downtime in factories, and to allow companies to monitor and control processes and systems for increased efficiency and enhanced profitability. The technology goal is reduction of the cost of

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[10] J.M. Kahn, R.H. Katz and K.S.J. Pister, "Next Century Challenges: Mobile Networking for "Smart Dust"," in Proc. Mobicom, Nov. 1999

[11] B. Warneke, M. Last, B. Liebowitz and K.S.J. Pister, "Smart Dust: Communicating witha Cubic-Millimeter Computer," in Proc. IEEE Vol: Number:, pp. 8, Jan. 2001

deploying, installing, and managing a sensing and control network. The self-configuring network requires no site survey, no RF knowledge, and no device-level management.

Figure 13: Commercialization

This completely wireless system (Figure 13) requires neither power nor communication wires. Devices can be completely untethered, creating opportunities in applications such as energy monitoring, HVAC systems, machine-health monitoring, and perimeter security.

In December 2004, Dust Networks was chosen from among 1200 nominations by Red Herring Magazine as one of their "Innovation 100" technology-based "companies to watch". Pister returned to UC Berkeley and BSAC full time in January, 2005 with a new appreciation of the challenges faced by BSAC industrial member companies in extending pre-commercial 'enabling' university research into commercially viable products.

9.3 Magnetic Immunosensor for Detection of Infectious Disease Exposure

A portable device suitable for handheld field deployment by moderately trained personnel has been developed and demonstrated[12]. This technology allows verified diagnostic assays for infectious diseases currently presenting significant threats to public health, including Dengue, Malaria, and HIV. The device has allowed dramatic simplification of testing protocol compared to ELISA (the current immunoassay standard) with special emphasis on the applicability of the assay in a point of care or at home setting, where the advents of a research laboratory are not available.

A high level of system integration is necessary for replicating the functionality of a diagnostic immunoassay protocol in an inexpensive, palm-held device. Sample preparation, segregation of specifically bound labels (those which match the suspected disease) from non-specific bound ones (those which do not match), and label detection present major obstacles to implementing an integrated immunoassay device (figure 14, Immunosensor).

Magnetic bead labels are particularly attractive in this context since they can be electromagnetically detected and manipulated in opaque solutions such as blood, where the optical Elisa method requires special laboratory sample processing . To leverage this advantage, a system was developed in which a functionalized Complementary Metal-Oxide-Semiconductor (CMOS) chip acting as the assay substrate can not only detect but actually count magnetic beads bound specifically to its surface via the target analyte and therefore quantify the degree of disease exposure. Non-specifically bound beads that would normally distort the overall bead count are removed by magnetic forces generated by currents flowing through on-chip conductors, a process which we refer to as "magnetic washing".

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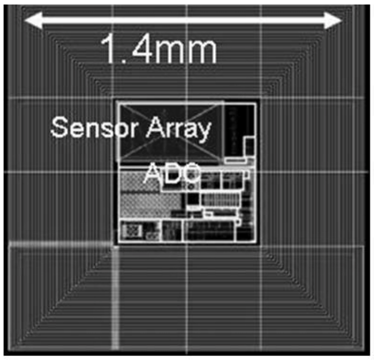
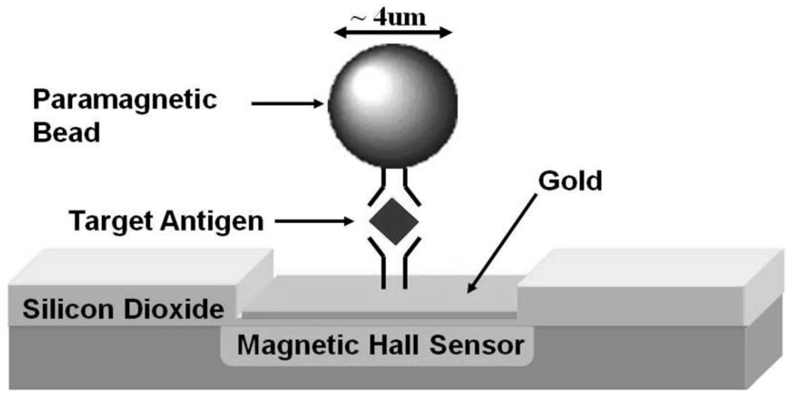
[12] T. S. Aytur, T. Ishikawa, and B. Boser, "A 2.2-mm2 CMOS bioassay chip and wireless interface," in 2004 Symp. on VLSI Circuits. Digest of Technical Papers, Gaithersburg, MD: Widerkehr and Associates, 2004, pp. 314-317

Figure 14: Immunosensor

With permission, Bernhard Boser



MEMS-Based Immunosensor Integrated Circuit (BSAC)



Immunosensor Magnetic Antigen Detection (BSAC)

The I/UCRC centered at UC Berkeley fostered aggressive partnering of the engineering school with the school of public health and department of molecular and cell biology and an external nonprofit institute to prepare for field trials for Dengue Fever detection in Nicaragua.

The integration of 1,024 Hall Effect differential magnetic sensors with local magnetic field generation for internally implemented magnetic washing of paramagnetic beads in a “system-in-package” assembly, with printed antenna for wireless access, represents system miniaturization and potential cost reduction (because of mass producible CMOS component) was unprecedented for complex field-or-home deployable assay. This magnetic immunosensor demonstrates feasibility of commercial development of very low cost, accurate, self-contained, rapid, field-deployed detectors for disease infections or exposures. The successful merging and resulting synergy of semiconductor electronics, MEMS, molecular biology, and health science research as revealed in this interdepartmental project is evidence of the benefits of multidisciplinary and interdisciplinary collaborations.

The results and demonstrations have attracted further research investment in the University by foundations and nonprofit institutes. A startup company Silicon BioDevices is led by the 3rd generation of BSAC researcher to have continued this research further toward commercialization readiness. PhD student graduate and cofounder Dr. Octavian Florescu has attracted interest from industry and venture sources with expectations of ultimate high volume commercialization. Early detection of targeted disease Dengue Fever substantially reduces risk of reinfections (that are far more lethal); and future home /anonymous detection of high stigma disease exposure e.g HIV promises to improve detection and early treatment, with consequent reduction of overall infection rates and national medical cost benefits.

8. Conclusions

BSAC, an NSF University-based Industry/University Cooperative Research Center has, over more than 25-years of continuous operation, demonstrated that top rank industry, academic, and government entities with dissimilar motives (profit vs information dissemination vs economic development) can exploit synergies and combine efforts in an Innovation Research model with goal realization for all parties and benefits to society as a whole.

The formalization and replication of the I/UCRC program by the National Science Foundation illustrates governmental program efficiency at its best.

BSAC
Berkeley Sensor & Actuator Center
The University of California BERKELEY
The University of California DAVIS
http://bsac.berkeley.edu

Figure Captions & Credits (by BSAC/J.Huggins unless otherwise identified):

Figure 1 Growth: Inspiration for Innovation *(Courtesy Richard M. White)*

Figure 2 One Generation of BSAC Alumni Circa 1990 *(Courtesy Richard S. Muller)*

Figure 3: Technology Readiness *(Adapted from NASA TRL Diagram)*

Figure 4: BSAC Symposium on Research-to-Commercialization

Figure 5: Funding Sources & Leverages

Figure 6: Research Synergies

Figure 7: BSAC Projects by Category

Figure 8: Research Syndication

Figure 9: Syndication Gain

Figure 10: (Removed)

Figure 11: MEMS Strain Gauge & Accelerometer for Vehicle Stability Control *(Courtesy Berkeley Micromechanical Analysis & Design Lab)*

Figure 12: BSAC Co-Director Prof. Kris Pister *(UC File Photo)*

Figure 13: Dust Networks Initial Platform *(Courtesy Dust Networks Inc.)*

Figure 14: MEMS Immunosensor *(Courtesy Bernhard Boser)*

[Figure 15: BSAC I/UCRC Logo w/Titling]

Table I: BSAC co-Directors

Tagle II: Industrial Member Organizations circa 2010

Table III: NSF I/UCRC Centers Statistics