Analysis of Value Creation and Value Capture in Microfluidics Market

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Acknowledgements

This thesis is a culmination of my professional interest and personal effort to bring clarity to business of microfluidics – an emerging and uncertain but potentially transformative technology in the life sciences. The motivation has its root in the hallmark process improvement efforts, of which I have had the privilege of being an integral part, at the Broad Institute. A four yearlong effort to optimize first generation sequencing process using microfluidics failed thrice. In the first two instances, the reasons were technical but in the last, also the most recent one, the reason was a mix of vendor's technology and market strategy. This piqued my interest to understand what and why of the microfluidics market. Quite humbly, this started as a simple hallway conversation. But, as it turns out, the interest followed me to System Design and Management (SDM) program, where it found its outlet in the form of well-deserved master's thesis. I am grateful to Pat Hale, Director of SDM program, for providing a rare opportunity through this program to gain firsthand experience in applying well-studied management frameworks and mental models for analyzing microfluidics market. Not only has this endeavor been deeply fulfilling but I also feel I have mastered the framework that will serve me well for the rest of my professional career.

The thesis journey began with a Technology Strategy course taught by Prof. Michael Davies in Spring 08. As he enthusiastically introduced our class to an array of powerful frameworks and demonstrated their utility through characterization of emerging mobile technologies, I knew I had found a set of tools for my thesis topic. I was very excited as he accepted my request to co-advise my thesis. I would like to acknowledge his frequent critical feedback, pointed suggestions and unique insights that have significantly refined the material. Even though I missed almost every deadline I set for myself, I feel fortunate to have an advisor who has been supportive despite the fact. I would also like to thank my co-advisor Prof. Todd Thorsen, who gave me unrestricted access to his microfluidics laboratory in Department of Mechanical Engineering. In addition, he was instrumental in helping me define the scope and refine the technical aspects of this thesis. Without the key insights from Prof. Noubar Afeyan, the thesis would not have been able to deliver - the main point and the strategic recommendations – as well as it does now.

I would also like to thank Robert Nicol, Director of Sequencing Operations, Broad Institute, who greatly helped me refine survey questionnaire and select thesis advisors. I would like to acknowledge Patrick Cahill, Director of Technology Exploration, my boss, who permitted me to attend two important conferences that gave me important access to opinion leaders, users and vendors in microfluidics. Without such access, the list of survey respondents would have been extremely limited.

I would like to thank my wonderful girlfriend, Inku Subedi, who provided many critical comments and feedbacks that helped improve this thesis significantly. She also kindly gave me access to Brown University Library, where I actually wrote most of the draft. And, my brothers, Jeetendra Yadav and Sanjay Yadav, and sister-in-law, Brenda Yadav, for being patient as I spent most of the holidays writing my thesis.

Finally, I would like to thank my parents, Ram Akwal Yadav and Usha Yadav, for permitting my extended absence from the long-distance phone conversations and providing me with their blessings.

Table of Contents

List of Figures

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By

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Submitted to System Design and Management on Jan 21, 2010
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Abstract:

Advances in microfluidics in the last two decade have created a tremendous technological value which is shaping genomics; drug discovery; proteomics; and point-of-care diagnostics. The positive impact has resulted in faster analysis time, increased throughput and reduced cost amongst other important benefits.

Yet, the life sciences end-users and the microfluidics players themselves are far from fully capturing the value. Author's own observation based on the experience at a leading genomics research institute, where multiple efforts to implement microfluidics technologies hardly succeeded, supports this fact. The failure to fully capture value has serious implications for the vendors developing microfluidics and the researchers employing these technologies. What are the reasons for this failure? What could be done to increase the value capture?

Using well-established management frameworks, such as, s-curve, adopter's distribution model, the thesis studied the nature of value creation and value capture. Survey was used to quantify the *impact* and the *diffusion and adoption* of microfluidics technologies, as the respective indicators of value creation and value capture. The data support the insight obtained from the conceptual frameworks that microfluidics is still an immature technology. It also shows that *immature technology* is the primary reason for lack of full value capture rather than the lack of killer application or niche market – commonly reported reasons in the literature. As an immature technology, microfluidics is thus far still only in the hands of users who are innovators and early adopters – the academic laboratories and the research institutes. The application segments which have seen the most value capture are *Genomics* and *Point-of-care diagnostics*. The application segment which has seen the least value capture is *Drug discovery*. This thesis concludes with the recommendations for short and long term strategies for increasing value capture and accelerating the adoption of microfluidics.

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1 Microfluidics Market

1.1 Overview of Market Size

The tremendous potential of microfluidics technologies is driving the growth of microfluidics market. According to (Gomez 2008), the size of the market for life sciences application reached $750 million in 2004. The market is expected to grow at a compounded annual growth rate of 13% to over $2 billion by 2010. (Gomez 2008) also states that the number of patents linked to microfluidics platform increased from under 25 in 1998 to over 350 in 2004. Based on the strategic analysis of biochips market in 2006 by Frost and Sullivan, the number of literature articles citing microfluidics technologies increased by an order of magnitude from about 10 in 1998 to about 740 in 2005 (Figure 1). The analysis predicted that the number will continue to increase in future as users follow proven experimental protocols employing microfluidics technologies.

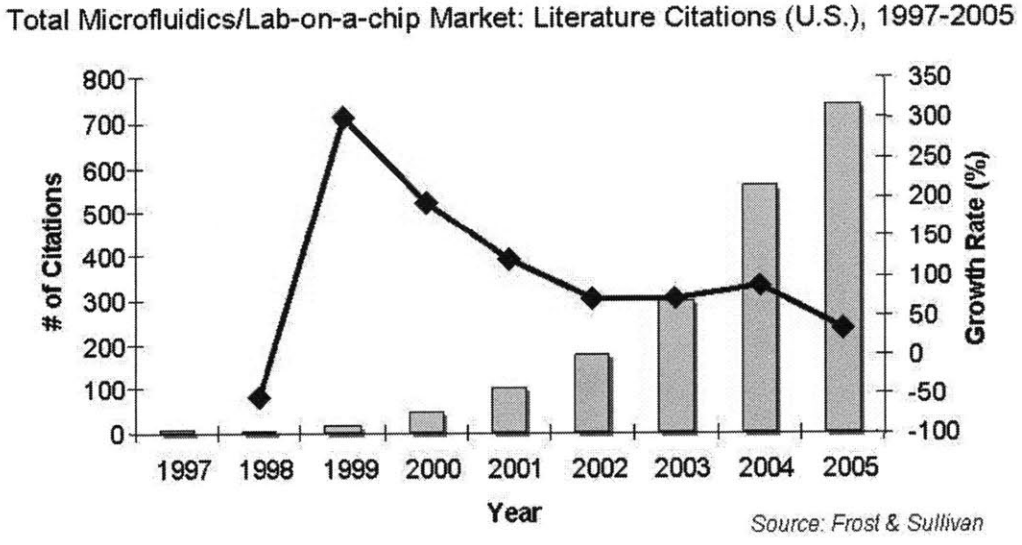

Figure 1. Literature Citations (US), 1997-2005, Source: Frost & Sullivan

1.2 Current State of Value Capture

Although the data clearly shows the extremely positive outlook of microfluidics market, the literature review of microfluidics market has revealed a different reality.

(Whitesides 2006) argues that microfluidics has a bright future but it is still in its early stage of development and cites two main reasons for lack of mass adoption by the end-users:

- First, although there have been considerable technology developments as proof-of-concepts in several applications due to the work of many researchers in the academic laboratory, there is a significant lag in the commercial development of products for the end-users.

- Second, there is a clear lack of killer application[1] to bring about a major success even though he lists early diagnosis of disease and diagnosis of response to therapy among potential high value applications to drive the field.

On the other hand, (Haeberle and Zengerle 2007) note that a significant market for microfluidics tools already exist in the academic laboratory itself. According to them, the developers of these tools are the end-users themselves, in search of novel applications in pharmaceuticals, biotechnology and diagnostics industries. They also identify the emergence of microfluidics platforms – an integrated systems approach to the field that is, now as a result, driving several spin-off companies.

The most recent study by (Mukhopadhyay 2009) cites Holger Becker of Microfluidics Chip Shop in Germany, who is also a microfluidics expert representing business issues in a *Lab on a Chip* journal. According to Becker, everyone predicted 10-15 years ago that a killer application would result in $100-300 million of total revenue. But, he describes the reality of that early prediction through Gartner Hype Cycle as shown in (Figure 2):

[1] Killer application is defined in *section 3.4.1* in *page 33*

- *Technology Trigger* occurred based on the early work by Andreas Manz – along with his colleagues – who is currently at University of Freiburg.

- This led to *Peak of Inflated Expectations* around late 90s, when microfluidics was widely predicted as a universal analysis platform.

- The peak followed by *Trough of Disillusionment* in early 2000 as microfluidics failed to deliver the promise it held since the hype began. But, at the moment, microfluidics is on the *Slope of Enlightenment*.

- Becker and other experts predict that in 5-10 years, it will reach the *Plateau of Productivity*. (Becker 2009) highlights the need for a killer application for commercial success of large capital intensive technology like microfluidics. He also notes that the success of microfluidics may be seen when niche market or killer application emerges during the plateau of productivity.

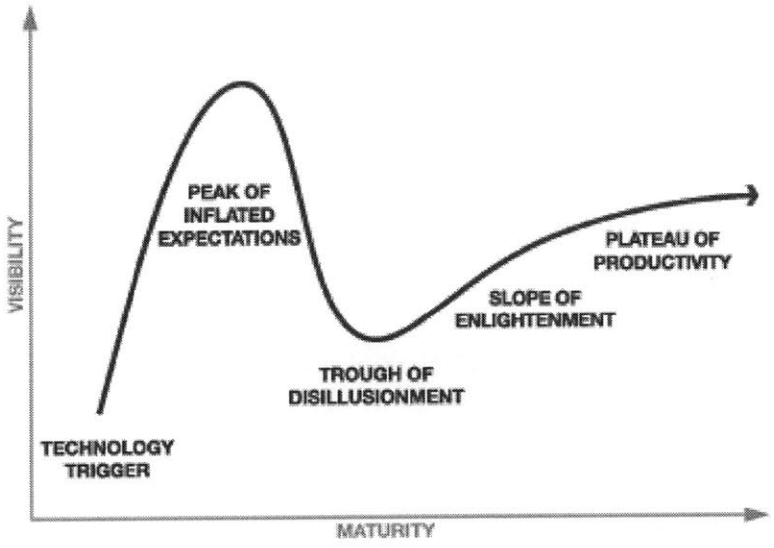

Figure 2. Gartner Hype Cycles, 2009, Source: www.gartner.com

Furthermore, (Mukhopadhyay 2009) cites a range of perspectives by the following experts to broaden the discussion of the future of microfluidics:

- Andreas Manz hints at the likelihood of microfluidics having no major success in the commercial market in the end even though it will continue to innovate in the academic laboratory.

- Based on his experience of watching four microfluidics companies, one of which is Raindance Technologies (www.raindancetechnologies.com), David Weitz at Harvard University points out that finding the right niche market has been the struggle of most of the companies and he re-emphasizes the importance of niche market for the success.

- Steve Soper at Louisiana State University is cautious about the optimism towards the clinical diagnostics application as a potential commercial market for microfluidics because of the lack of complementary technology. For instance, in case of cancer diagnostics, many molecular markers have not been approved by appropriate authorities like American Society of Clinical Oncology.

In addition, informal conversations with the microfluidics experts at Miniaturized Systems for Chemistry and Life Sciences (MicroTAS 2008) conference support the findings from the literature review. In addition, they also provide additional insights as described below.

- According to Todd Thorsen at Massachusetts Institute of Technology, Food and Drug Administration (FDA) regulation is one major obstacle in adoption of microfluidics by big pharmaceutical companies. This is because microfluidics devices are treated, in part, like medical devices. As such, they need to be validated in-house with biomarkers/reagents before being used to support drug discovery activities. The validation presents both technical and economic risks, which most companies are unwilling to take.

- Harold Craighead at Cornell University points out that one of the issues with microfluidics is the lack of killer application. He adds that for microfluidics to succeed the focus should not only be on the miniaturization but it should also be on new approaches to detection and analysis along with novel surface chemistries.

- Andrew Griffith at Institut de Science et d'Ingénierie Supramoléculaires (ISIS) also agrees that microfluidics has not yet found the killer application. He also thinks this I an important reason for the limited success of microfluidics.

1.3 Motivation for Further Study

In conclusion, the studies and interviews broadly inform the current state of microfluidics. They also offer a glimpse into the future through the experiences and the perspectives of the experts in the field. While everyone agrees on the tremendous value that has been created by the microfluidics technologies, almost all think that the commercial market remains far from fully capturing the value due to the lack of mass adoption by the end-users. While the studies present most up-to-date qualitative analysis, it doesn't provide quantitative data on value creation and value capture in the market. This thesis aims to fill this gap in the following ways. First, it will apply conceptual and analytical frameworks to study the microfluidics ecosystem to offer deeper insights into innovation, diffusion and adoption of microfluidics technologies. Second, it will collect and analyze data from the end-users to offer quantitative perspectives on the current state of diffusion and adoption. Finally, it will make strategic recommendations to increase the value capture for end-users and developers alike.

2 Microfluidics Technology

2.1 Overview

Microfluidics is an emerging area of study about theory and applications of low volume fluids for applications ranging from ink-jet printer to point-of-care diagnostics chip. The focus of this thesis, however, is limited to applications of microfluidics in life sciences. The scale of microfluidics volumes and sizes used in the most of the common applications today is shown in (Figure 3).

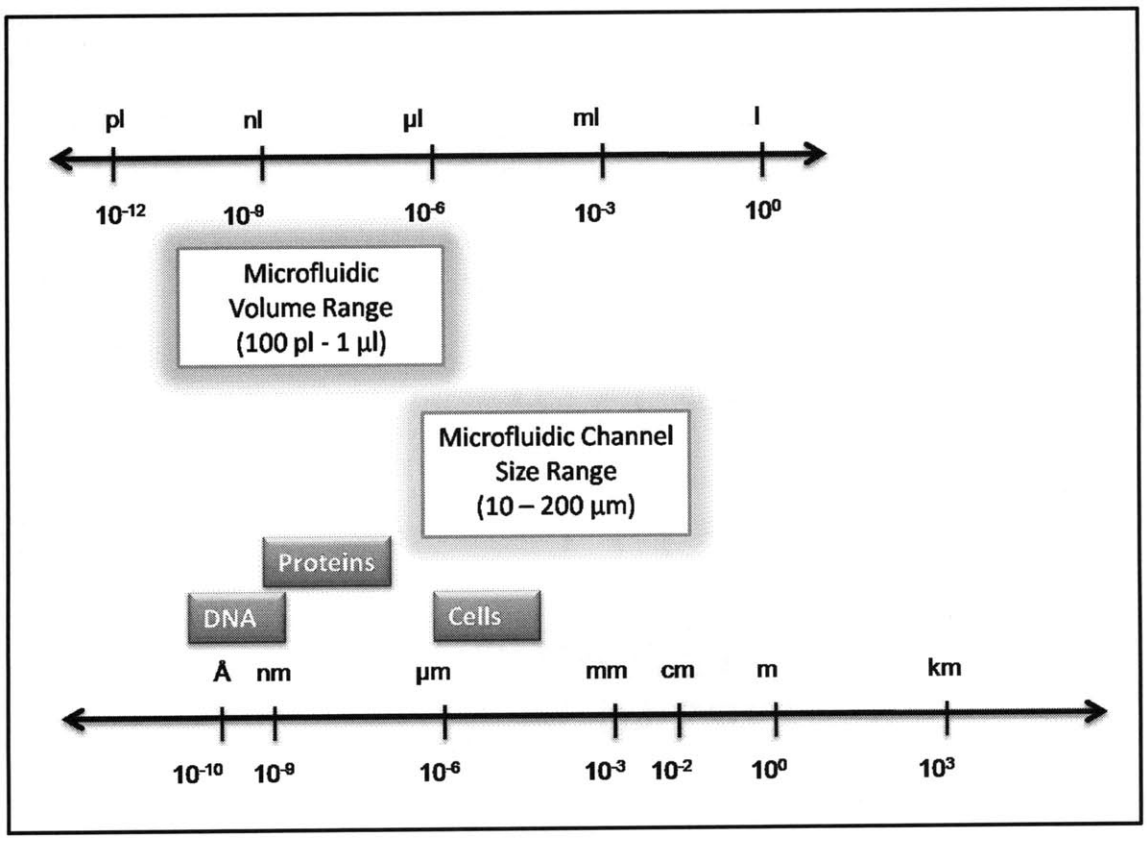

Figure 3. Microfluidics Scale

Microfluidics is a highly interdisciplinary field which integrates material science, physics (fluid mechanics and optics, in particular), biology, chemistry and engineering to create a common enabling technology platform for a variety of applications. With important benefits (*Section 2.8*

Key Benefits) under its belt, this single enabling platform has created a tremendous value for the initial end-users with unique needs that cannot be met with current technology. Today, microfluidics-enabled applications are rapidly advancing the fields of genomics, drug discovery, proteomics and point-of-care diagnostics due to the unparalleled benefits offered by microfluidics technologies. The list of benefits includes cost reduction, scalability, and portability among many others. The technology is able to deliver aforementioned benefits by manipulating extremely low volume fluids inside the microfluidics components, such as pumps, channels, mixing units, etc as described in *Section 2.3 Systems View*. The manipulation of the fluids enables an important step in any biochemical assay – sample preparation. Sample preparation and detection steps (Figure 4), further enable applications ranging from screening for a drug candidate in a drug discovery process to obtaining one's genetic profile in a point-of-care diagnosis step.

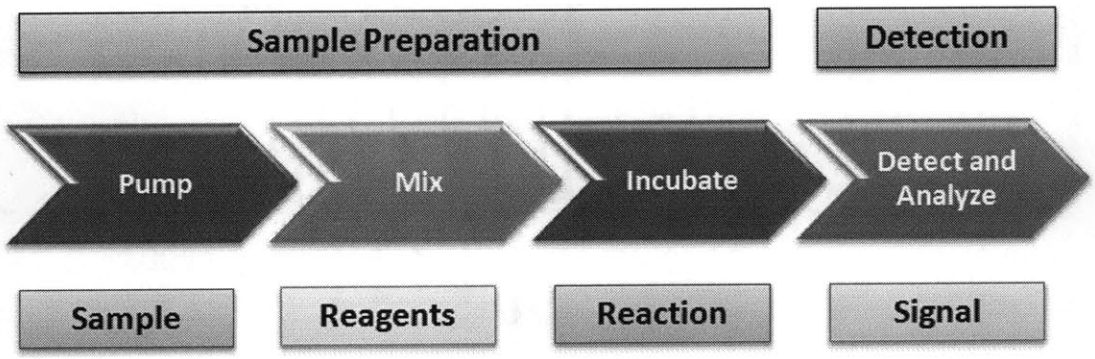

Figure 4. A Typical Microfluidics Process Steps

2.2 History

Microfluidics became a popular technology in the life sciences community after the early work done by (Manz, Harrison et al. 1992) led to the explosion of patents, publications and further research into this area as noted by (Mukhopadhyay 2009). Although the technology has grown considerably in the last decade to address the needs of new applications in life sciences, the emergence of this technology have occurred much earlier in the form of capillary strips for

diabetes and pregnancy test in 50s (Haeberle and Zengerle 2007). The innovations in semi-conductor fabrication techniques in 60s, 80s and 90s were the key enabling technologies for the accelerated growth of microfluidics. The timeline of microfluidics development is shown in (Figure 5).

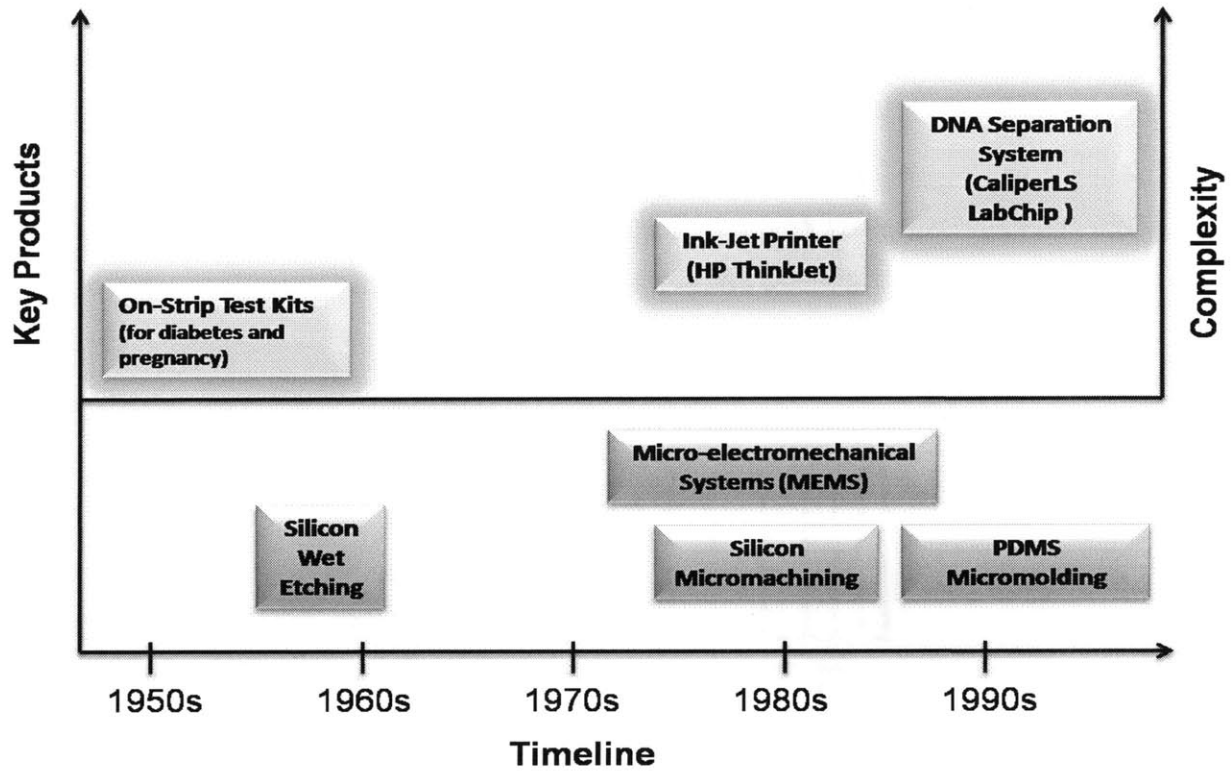

Figure 5. Timeline of Key Enabling Technologies

These enabling technologies led to the development of one of the most commercially successful microfluidics product, albeit outside the life sciences domain, HP ThinkJet inkjet printer (www.hp.com). Introduced in early 80s by Hewlett-Packard, the inkjet printer forever transformed the printing process from slow, low-quality and noisy dot-matrix printing into a fast, high-quality and quiet ink-jet printing. In the late 90s, life sciences market received the first commercially successful microfluidics product in the form of Caliper Life Sciences' LabChip System, 2100 Bioanalyzer (www.agilent.com). The product offered a single platform for DNA sizing, separation and quantification for DNA, RNA, proteins and cells (www.genome.gov). It

also offered other significant benefits of speed, ease-of use, ready-to-use assays and kits over conventional gel technology.

2.3 Systems View

A microfluidics system is a key enabling technology in microfluidics based products. A microfluidics system is comprised of various types of microfluidics components, which are structurally and functionally connected to achieve unique goals of different applications. The high-level system architecture of a typical product using microfluidics is shown in (Figure 6). Most applications require some or all of the following indispensable functionalities – pumping (for delivering sample), mixing (for adding and mixing with reagents), incubating (for reaction to occur) and detecting (for reading and analyzing signals). The functionalities are provided by the respective microfluidics components: pump and channels; mixing unit; reaction unit; and detection optics.

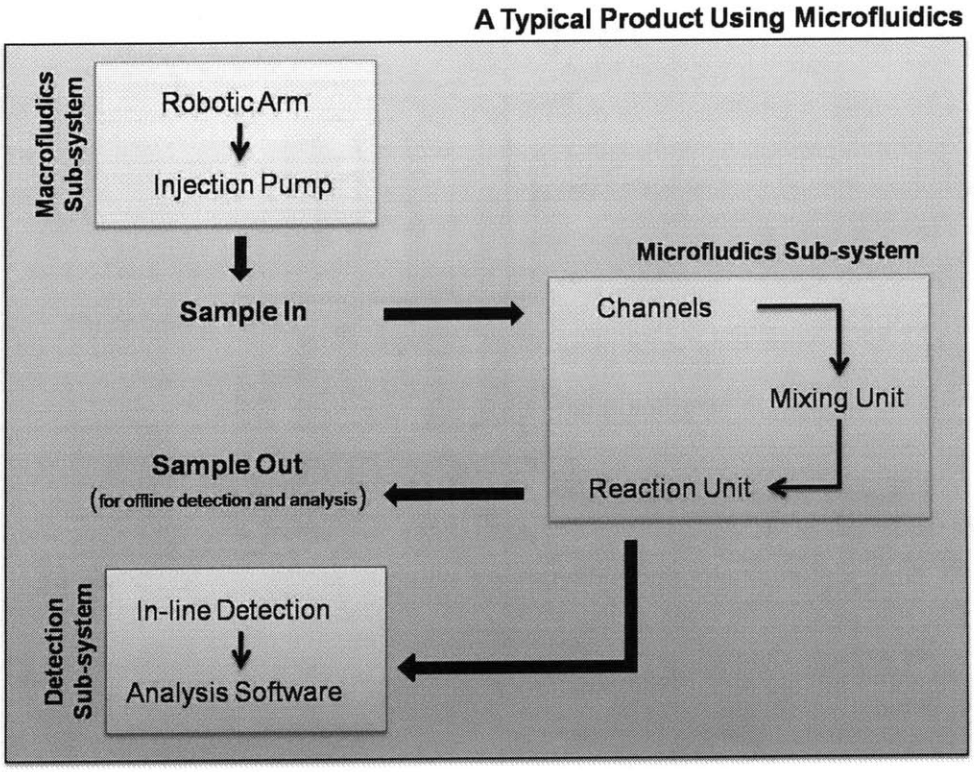

Figure 6. System Architecture of a Typical Product Using Microfluidics

The system level operation begins inside the macrofluidics sub-system with an actuation of robotic arm, which picks up a sample from a reservoir. The injection pump then drives the sample and reagents into microfluidics sub-system. Inside the microfluidics sub-system, the sample and reagents flow through a network of channels. The mixing unit provides mixing operation prior to biochemical reaction inside a reaction unit, where the precise reaction volume is defined through high degree of flow control offered by precision pumps. After the reaction is complete, the detection sub-system collects the data using sophisticated optics and feeds them into analysis software for delivering the results of the analysis.

The architecture of microfluidics systems can be characterized by two factors – *complexity* and *modularity*, which segments products into each of the four quadrants of architectural framework shown in (Figure 7).

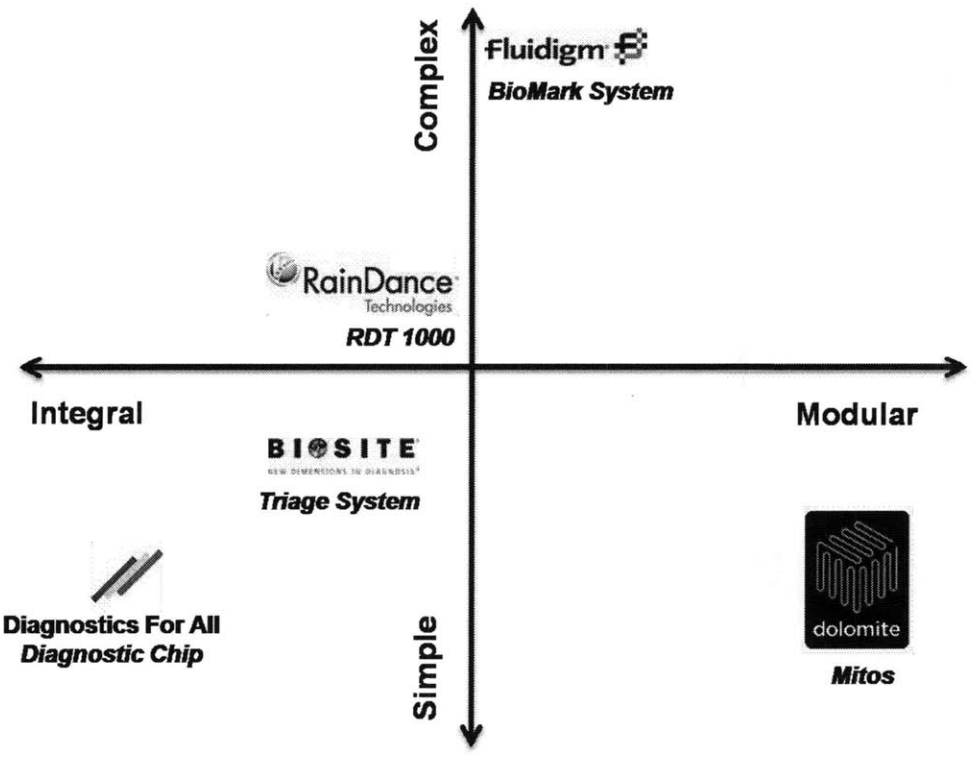

Figure 7. Microfluidics Product Architecture Framework

(Crawley 2008) defines complexity as *"Having many interrelated, interconnected or interwoven elements and interfaces"* modularity as a system comprising of modules, which according him are *"collections of (1...n) parts which are defined by some intent to be a distinct system"*. Consistent with this definition, Fluidigm's BioMark (www.fluidigm.com) is highly complex but moderately modular. The system has 9216 reactors, with interconnected fluidic lines, which run 9216 parallel Polymerase Chain Reactions (PCR) (www.genome.gov). It also has several modules – reactor, fluidics, optics, control software analysis software, and motion control. In contrast, DiagnosticForAll's diagnostic platform (www.dfa.org 2009) is simpler and embodies integral architecture. Although the exact number of assays wells is not disclosed, the published material on the website notes the device is very simple has only has a single module – paper chip.

To offer a deeper systems perspective of microfluidics product system, (Dori 2002)'s Object Process Methodology (OPM) tool is used to describe the architecture of Raindance Technologies' RDT 1000, a leading microfluidics product used for generating microdroplets containing libraries of DNA molecules in genomics application. As shown in (Figure 8), this characterization of the system architecture begins with the translation of product *intent* into a description of the *problem*, which is *efficiently generating single molecule DNA libraries*. The *solution* to address the problem includes the high-level concept, which maps the function – *dropletizing* – onto the form – *DNA molecules*. At a low-level, the concept represents stable dropletizing of bulk DNA molecules using a small footprint microfluidic chip inside a microfluidics system. Finally, the solution is supported by imaging system, motion control system and control software in the context of RDT 1000.

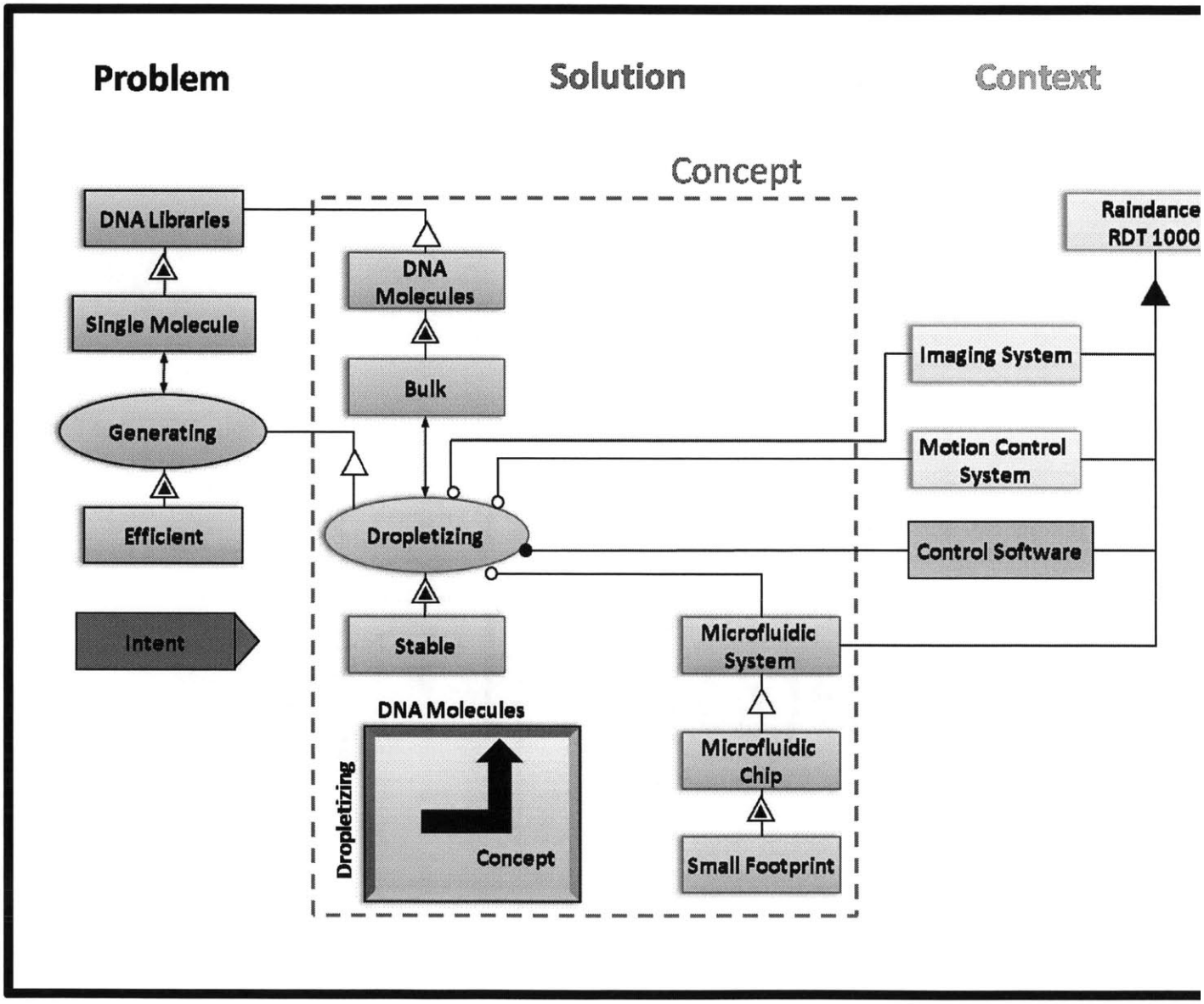

Figure 8. System Architecture of RainDance RDT 1000 System

The RDT 1000 instrument and disposable chip for targeted sequencing application are shown in (Figure 9).

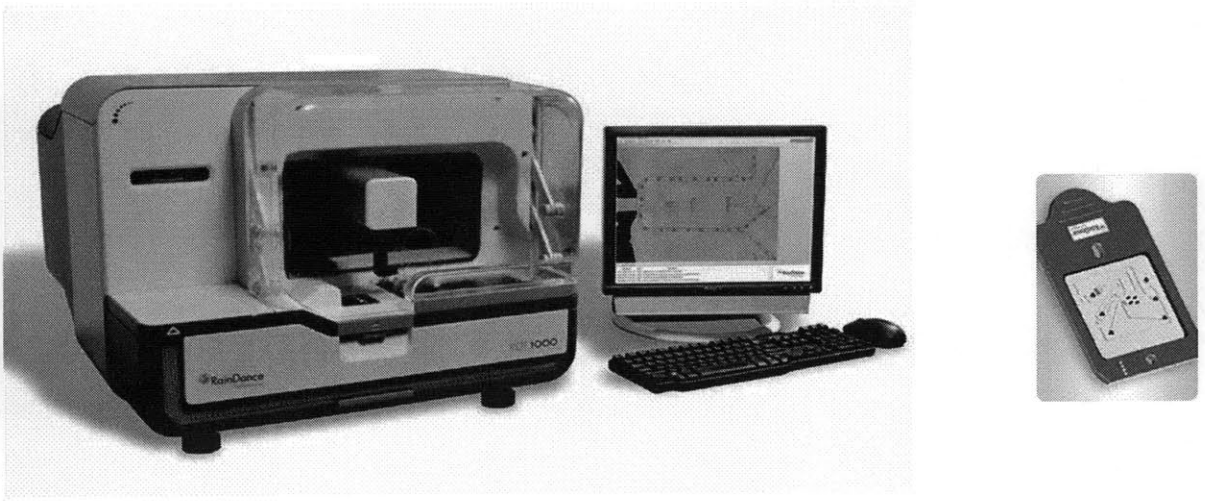

Figure 9. RDT 1000 Instrument and Disposable Chip (Courtesy:Raindance Technologies)

2.4 Technology Innovation

Microfluidics has been on the path of continuous innovation since its emergence. This innovation can be captured by following key innovation parameters as shown in (Figure 10) and the innovation trends as described in *Section 2.6 Innovation Trends*.

2.5 Innovation Parameters

Microfluidics technologies innovation can be captured by two key innovation parameters, which have evolved over time as shown in (Figure 10).

1. Sample Volume – Microfluidics emerged with continuous bulk fluid flow, which enabled inkjet printing in Hewlett Packard ThinkJet. A typical sample volume required was > 200

μl (due to a large dead volume in the ink cartridge)[2]. However, with the advent of droplet microfluidics, the sample volume required is > 10 μl. This has enabled those applications requiring single molecule amplification or single cell analysis became possible (Teh, Lin et al. 2008). For instance, Raindance Technologies' RDT 1000 (www.raindancetechnologies.com) uses droplet microfluidics technologies to create libraries of single DNA molecule in droplets for sample preparation in the next generation sequencing.

2. Number of Reactions – A large number of reactions makes a parallel analysis possible. While isolated channels on silicon or glass enabled a handful of reactions, the Integrated Fluidic Circuit (IFC) architecture (www.fluidigm.com) enabled massively parallel reactions without increasing the space requirement. For instance, Fluidigm's BioMark system allows a user to run 9,216 quantitative PCR reactions in the same amount of time and footprint compared to a standard 384 well plate (www.sigmaaldrich.com).

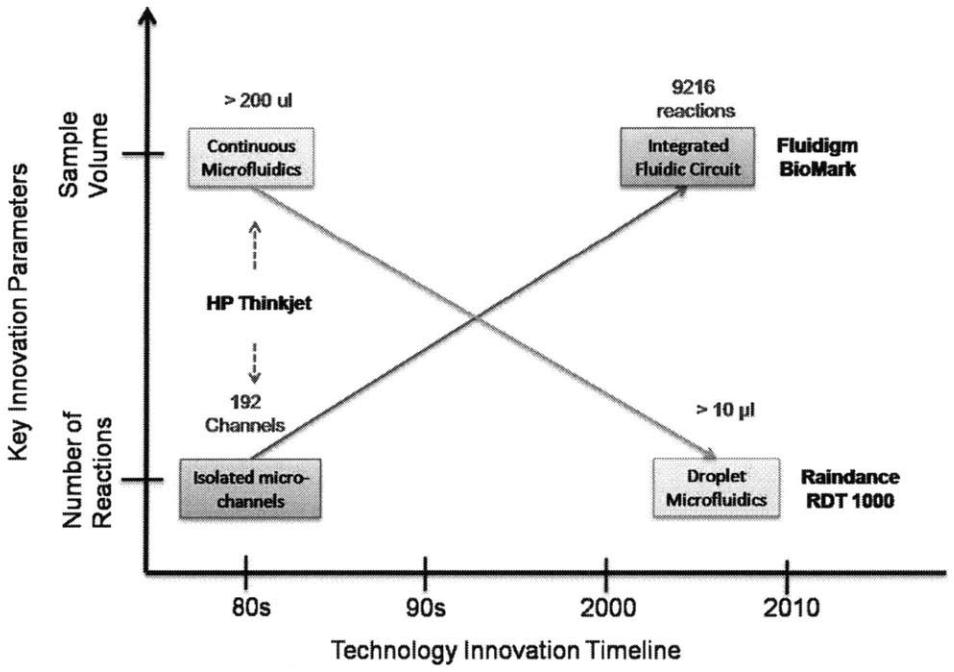

Figure 10. Evolution of Key Innovation Parameters

[2] The dead volume is based on the piezoelectric ink-jet cartridge in Fujifilm Dimatix Printer and Cartridge (http://www.dimatix.com/files/printer_faqs.pdf)

2.6 Innovation Trends

There are two important innovation trends in microfluidics.

1. Fabrication Innovation – The ink jet printing in Hewlett Packard Thinkjet (www.hp.com) was enabled by silicon wet etching in 80s. On the other hand, in the 90s, the novel applications like digital PCR, gene expression and genotyping (www.genome.gov) have been enabled by multilayer soft lithography (Unger, Chou et al. 2000), using Fluidigm BioMark system (www.fluidigm.com; www.genome.gov)

2. Architectural Innovation – Microfluidics was a dominant technology in Hewlett Packard Thinkjet. But, microfluidics has gradually evolved into an "enabling technology" in new microfluidics based products. For instance, Illumina's Genome Analyzer System (www.illumina.com), a next generation sequencing product, uses microfluidic flowcell chip – an enabling technology – for massively parallel sequencing reactions.

2.7 Technology S-Curve

The innovation trajectory of microfluidics technologies can be represented by technology S-curve as shown in (Figure 11). The S-curve captures a *radical innovation,* which evolves over time as an *incremental innovation*. (Henderson and Clark 1990) have noted that the radical innovation requires new set of design and engineering principles, which has significant impact on the system components. Incremental innovation, on the other hand, is an improvement upon the existing component designs based on the same design concepts. Furthermore, (Bowden 2004) splits technology s-curve into four distinct phases. Any innovation begins with the new invention followed by significant technology improvement. Then there is a transition into the third phase, where technology matures and after a while, it ages into the fourth phase.

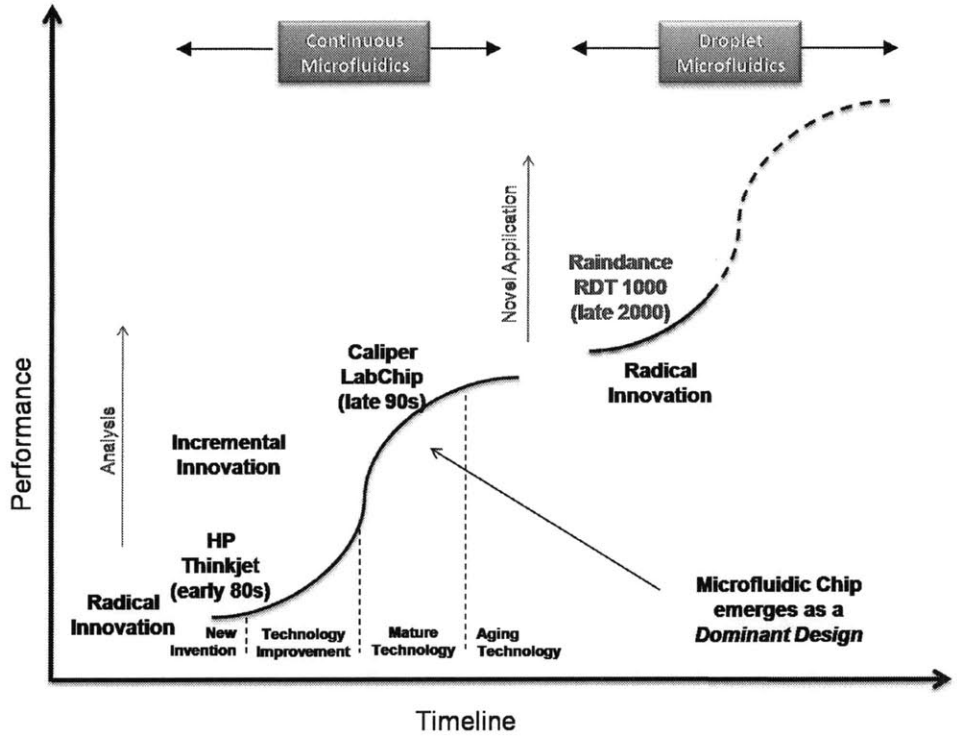

Figure 11. Technology S-Curve

The innovation in microfluidics technologies emerged with the radical innovation of *continuous microfluidics* – microfluidics of bulk sample and reagents (Figure 12). This is represented by the first S-curve. The innovation in semi-conductor fabrication technologies – in particular, silicon wet-etching – enabled the microfluidic inkjet cartridge. This led to the birth of inkjet printer at Hewlett Packard. The technology improved significantly and reached the mass market in the same decade. Driven by the needs of life sciences, microfluidics underwent significant improvement from a simple tool for enabling rapid printing to a powerful tool for biomolecule analysis. This led to a highly successful and a mature product known as Caliper LabChip system, which is used to perform separation and analysis of DNA. But, microfluidics has gone through more than one radical innovation. According to (Bowden 2004), multiple radical innovation are represented by corresponding sets of S-curves.

The second S-curve represents a second radical innovation – *droplet microfluidics*. As the name suggests, droplet microfluidics (Figure 12) is microfluidics of droplets, which encapsulate

individual biochemical molecule. This brings radically different applications, not realizable with continuous microfluidics, within the reach of microfluidics technologies. Targeted sequencing application is a good example, in which a target gene of interest is merged at a high speed with a PCR reagent for sequence enrichment application. By isolating a single gene inside a droplet, droplet microfluidics has eliminated the bias associated with PCR amplification when multiple genes are used during the amplification. Raindance Technologies' RDT 1000 is a commercial product which offers targeted application for genomics end-users.

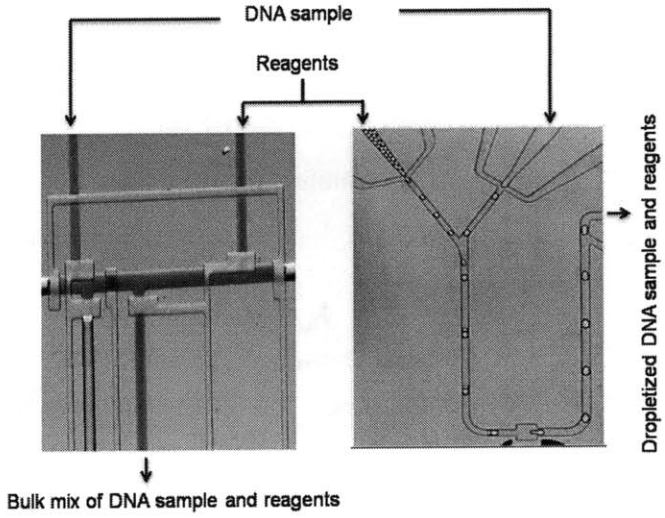

Figure 12. Continuous and Droplet Microfluidics

2.8 Key Benefits

The ongoing technological innovation has made microfluidics a powerful technology. As a common enabling platform for variety of applications in life sciences, microfluidics offers following key benefits.

1. Faster analysis time: Because of streamlined end-to-end process, along with highly integrated on-line detection system, microfluidics system is able to perform faster analysis compared to that of the conventional system. For instance, by automating sample preparation, Caliper LS's LabChip GX platform provides high resolution analytical data

approximately 50 times faster compared to that of manual gel based separation. Faster analysis time enables quick R&D turnaround time.

2. Higher throughput: Microfluidics systems offer highly scalable architecture that makes a significantly large number of parallel reactions possible compared to that of the conventional technology. For instance, it is possible conduct 23 times more quantitative PCR reactions using Fluidigm BioMark product compared to that of a standard 384 well plate. The parallelization reduces the variations typically seen in batch processing of samples.

3. Low sample/reagent volume: Through the use of micro-components, microfluidics has miniaturized reactions down to the volume ranging from few hundred nanoliters to a microliter. By reducing the volume of typical reactions in genomics assays, it is possible to reduce evaporation and other losses of valuable samples and reagents. This results into a potential volume reduction of up to 50% or more. This is very important where amount of sample available is highly limited (e.g. a rare tumor sample).

4. Reduced reaction cost: A lot of reagents used in important assays in genomics, proteomics and drug discovery are very expensive. Because of the reduction of reaction volumes, it is possible to perform large number of reactions at the same cost. The cost savings varies depending on the application.

5. Small Footprint/Portability: The miniature and light weight microfluidics components, along with highly scalable architecture, enable microfluidics to offer portability for mobile applications and small footprint for space-constrained laboratories.

6. Single cell/molecule analysis: Droplet microfluidics has enabled encapsulation of a single cell in a droplet. This has an important implication for single cell assays, which was hitherto impossible to perform. For instance, it is now possible to determine the dosage requirements of a large number of drugs more accurately and at a significantly high-throughput for the treatment of a genetic disease like cancer.

3 Demand Opportunity

3.1 Demand Generation

As described in *Chapter 1*, the initial wave of publications and intellectual properties in microfluidics during early 90s set the expectations from this budding technology extremely high. The expectations were justified, in part, due to the demonstrated potential of this technology to transform the research, development, and commercialization of biomedicine through miniaturization of a range of applications in genomics, proteomics, and drug discovery. Specifically, microfluidics has enabled two areas, which as a part of positive feedback loop, are subsequently driving the demand generation of microfluidics technologies. The two drivers are shown in (Figure 13).

The first driver is the *Process Improvements,* which include projects to reduce cost, improve data quality and increase throughput in existing customer applications. A microfluidics system used in such process improvement projects is popularly known as a *lab-on-a-chip* system. As it became clear that microfluidics would permit the development of highly portable systems, the second driver – *Novel Applications*, like the point-of-care diagnostics, is driving the further demand.

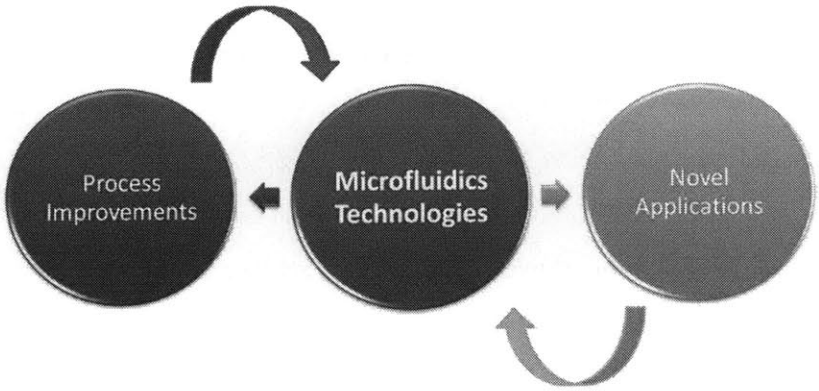

Figure 13. Positive Feedback Loop of Microfluidics technologies Demand Generation

3.2 Customer Segments

There are two major customer segments that are generating the demand for the microfluidics technologies as shown in (Figure 14). The first segment is *industry*, which comprise of tool vendors, who use microfluidics in two primary ways. First, it is used as an enabling technology inside a product that is intended for a specific application. For instance, Illumina uses microfluidic flow cell inside Genome Analyzer product for genome sequencing application (www.illumina.com). Second, it is used as a microfluidics platform inside a product. For instance, Raindance Technologies, which uses microfluidic chip, in conjunction with other sub-systems inside RDT 1000 as a platform technology for targeted genome sequencing and a host of other applications like bacterial screening.

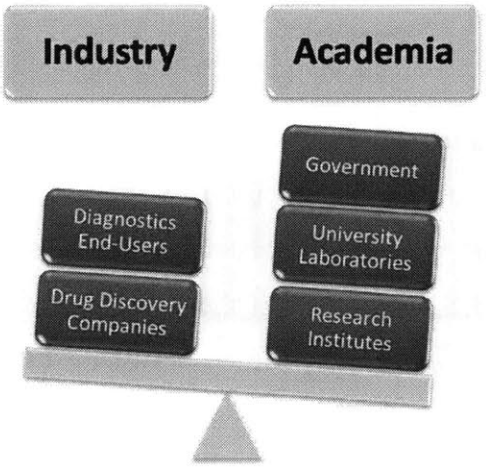

Figure 14. Customer Segments

The second customer segment, *academia*, comprises of research universities, independent research institutes and government. Academia is the "lead user" of microfluidics technologies. According to (Hippel 2005), a "lead user" is ahead of most of their peer users with respect to market trends. These lead users expect to benefit greatly from the solutions they develop for their needs. But the products that are developed by these lead users are highly likely to be adopted by their peers over the time. By the virtue of the volume of microfluidics applications being developed by a large number of researchers, this customer segment also significantly outweighs

industry in terms of microfluidics technologies development and adoption. The research universities usually develop their own microfluidics tools in-house for research and development. But they also purchase standard microfluidics products from tool vendors for standard applications like DNA quantitation and sizing. The independent institutes, on the other hand, typically only buy microfluidics products from tool vendors although some collaborate with academic labs for technology transfer and integration. For instance, while Broad Institute (www.broadinstitute.org) has purchased Illumina Genome Analyzer for genome sequencing, it has collaborated with Professor Todd Thorsen's laboratory[3] at the Massachusetts Institute for Technology for genome sequencing sample preparation improvement.

3.3 Application Categories

Emerging applications are driving innovation in life sciences. There are four broad categories of applications that are being enabled by microfluidics technology as shown in (Figure 15).

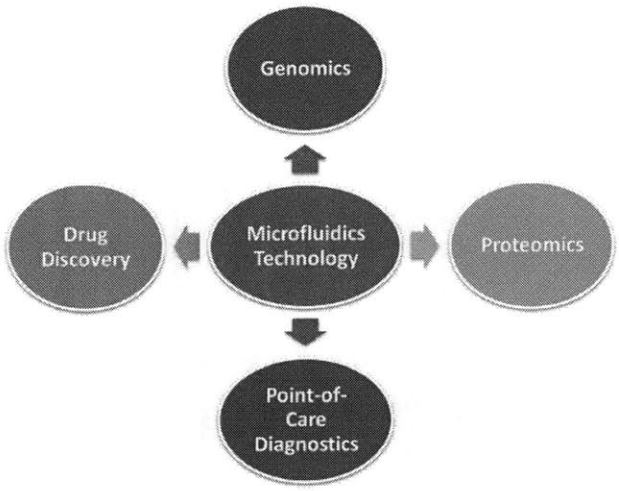

Figure 15. Microfluidics Applications

1. Genomics: The successful completion of Human Genome Project (www.genome.gov) in 2001 accelerated genome sequencing, genotyping, gene expression and DNA/RNA

[3] http://web.mit.edu/thorsen/www/

analysis applications in genomics. Microfluidics is a key enabling technology in genome sequencing. For instance, microfluidic flowcell and picotiter plate have enabled millions of parallel sequencing reactions in next generation sequencing in Illumina Genome Analyzer and 454 Genome Sequencer (www.454.com)) respectively. Similarly, dynamic array chip has enabled 9,216 parallel reactions for genotyping and gene expression in Fluidigm BioMark (www.fluidigm.com).

2. Proteomics: Proteomics cover large-scale study of proteins to determine their structures and functions. The key proteomics applications are matrix-assisted laser desorption ionization (MALDI) mass spectrometry (Julie 2007), protein crystallization, enzyme-linked immunosorbent assay (ELISA) (Lequin 2005). Fluidigm BioMark is a microfluidics product which has enabled protein crystallization. In addition, there are ongoing developments in academia that support MALDI (Lee, Soper et al. 2009) and offer microfluidics alternative to ELISA (Dupuy, Lehmann et al. 2005) for increased cost and time savings.

3. Drug Discovery: Drug discovery is the first stage in a typical drug development process which eventually yields one drug – usually after a decade of development timeline and almost a billion dollar expenses – which offers cure for a target disease. One of the most critical steps at this stage is high-throughput screening (HTS) of millions of candidate drugs to pick a lead drug for further development. (Maerkl 2009) lists a number of approaches for performing HTS using microfluidics technologies. (Thorsen 2004) describes one specific approach using a silicon microfluidic array chip for high-throughput single cell assays.

4. Point-of-Care Diagnostics (POC): POC applications primarily include cheap and quick diagnosis of infectious or genetic diseases in decentralized hospitals or rural areas without sophisticated analytical systems. (Wei Yi 2007) notes POC applications are in need of portable automated microfluidics systems, which require least amount of sample to deliver the results quickly.

3.4 Diffusion and Adoption

The adoption of microfluidics technologies by the end-users in two customer segments *(Section 3.2 Customer Segments)* is necessary for microfluidics technologies to meet end-users' demand. The rate of adoption by these end-users is reflected in the pattern of diffusion of microfluidics technologies. The diffusion of microfluidics technologies in the last decade can be best described by *probit adoption model*, which is based on the premise that heterogenous users have different goals and needs and the adoption occur at different times (Geroski 2000). With different application needs *(Section 3.3 Application Categories)* and priorities, microfluidics users will adopt microfluidics technologies at different times using probit model.

3.4.1 Key Factors in Diffusion and Adoption

There are then the following eight key factors – also the characteristics of a product – which influence the rate of adoption and diffusion of microfluidics technologies.

1. Availability of Application: Ultimately, the availability of application (for a new technology) is necessary for a technology to enter market and to succeed in terms of increasing sales. The ideal application is a killer application, which according to (Becker 2009) was coined in 1980s to describe applications in software industry with highly desirable properties described below:

    - The sale of killer application results in increased revenue – in the range of hundreds of millions of dollars – with high margins quickly attained.
    - A killer application drives underlying technology's adoption to gain bigger market share.
    - A killer application not only benefits a single manufacturer but also, in fact, the whole market segment.

In addition, (Dasgupta 2002) describes the features of killer application as *"A killer application has to be exceptionally appealing, amazingly useful and totally simple"*. While in software he lists Visicalc – the earliest spreadsheet program developed in 1979 – as an example, he also cites a telephone, email and radio as examples of other non-software killer applications.

2. Definition of Market: A niche market plays an important role in technology's success. (Shani and Chalsani 1992) defines niche market as a subset of a market with unique needs that can be met with a technology or a product. A niche market is of sufficient size, offers profitability for a company, and has a growth potential. But since this market requires specialized skills and resources to tap into, it poses a high barrier to entry. This makes it unappealing to the competitors.

3. Maturity of Technology: The maturity of technology relates to its stage of development after the innovation occurs. The innovation occurs primarily in the form of conceptualization of an idea and proof-of-concept experiment. During the improvement phase, a technology typically moves, and often cycles through: alpha and beta stages before it enters the commercial market. The technology becomes mature once the improvement phase is over (Bowden 2004). Users are more likely to adopt a product which is mature.

4. Cost of Implementation: The cost of implementation of a novel technology includes the cost of purchase, testing and validation, training and opportunity cost. The higher cost to implement typically meets with resistance unless the value returned is significantly high.

5. Advantage over Current Technology: The new technology must have unique advantages that would result into significant payoffs for the users. The uniqueness of advantages compared to that of current technology makes the technology highly favorable for adoption.

6. Adoptability: A new technology must be adoptable. The adoptability reflects users' willingness to adopt, which typically depends on the individual preference, group culture and the level of user innovativeness. Adoptability is critical in exploration, evaluation, and implementation of a new technology.

7. Challenges in Implementation: Implementation of new technology often poses both anticipated and unanticipated challenges. Overcoming such challenges can be costly, time consuming, and may even lead to unintended outcome, such as, total failure. Users are more likely to adopt a technology with fewer challenges that are well-understood and addressable.

8. User Friendliness: User friendliness refers to the ease of interaction with a new technology hardware and software. Users are typically resistant to behavior change. The technology with least amount of behavior change has the highest potential for adoption.

3.4.2 Key Drivers of Diffusion and Adoption

The diffusion and adoption of microfluidics technologies is driven by two important drivers *(Section 3.1 Demand Generation)* as shown in (Figure 13).

The first driver, *Process Improvements*, reflects a typical microfluidics user's *exogenous needs* – needs which arise in response to user expectations over time and broad societal shifts (Davies 2008). For instance, there is a need for generation of high quality biopharma process data in a short amount of time and at a lower overall cost by improving current drug discovery process. This process improvement need is driven by the following three factors: decreasing R&D budget due to stagnant government funding in recent years, decreasing number of successful drugs in the market in the last decade and increasing healthcare cost due to aging population.

The second driver, *Novel Applications*, on the other hand, reflects a typical microfluidics user's *endogenous needs*- needs which arise due to user's own changing beliefs in response to

technological innovation (Davies 2008). The need for novel applications is driven by the emergence of new possibilities. For instance, quick and cheap diagnosis of an infectious disease in a rural areas, which lacks centralized hospitals with sophisticated analytical systems.

3.4.3 Rate of Adoption

The key factors in Section 3.4.1 can be used to predict the likelihood of diffusion and adoption of microfluidics technologies. But, the actual rate of adoption (of microfluidics technologies), can be explained using the adopter distribution model (Figure 16) developed by Everett Rogers in 1957 for studying the diffusion of innovation in agricultural technologies (Rogers 2003). He argued that his model is a universal process, which was later applied to cellular and internet technologies in 90s. According to him, the adopter distribution, which reflects the characteristics of a user, follows bell curve over a time and approaches normality. It can be divided into five categories – innovator (2.5%), early adopter (13.5%), early majority (34%), late majority (34%) and laggard (16%).

Innovators possess high degree of knowledge about the technology and take substantial risk in adopting an innovation. They are also comfortable with uncertainty.

Early adopters rely on the decision made by innovators to make their own decision about the adoption. They make well informed decisions based on the well-respected opinion leadership, most of which is available among early adopters themselves.

Early majority take long time to adopt an innovation and as such wait until the innovation is proved by the early adopters. They are the followers of innovation instead of being the leaders. They have some access to opinion leadership.

Late majority are skeptical about new innovation and adopt based on the economic necessity and peer pressures. The technology has to be improved beyond uncertainty stage for late majority to adopt.

Finally, the *laggards* may resist adoption until everyone before them has adopted an innovation. They have no access to opinion leadership and have very limited resources.

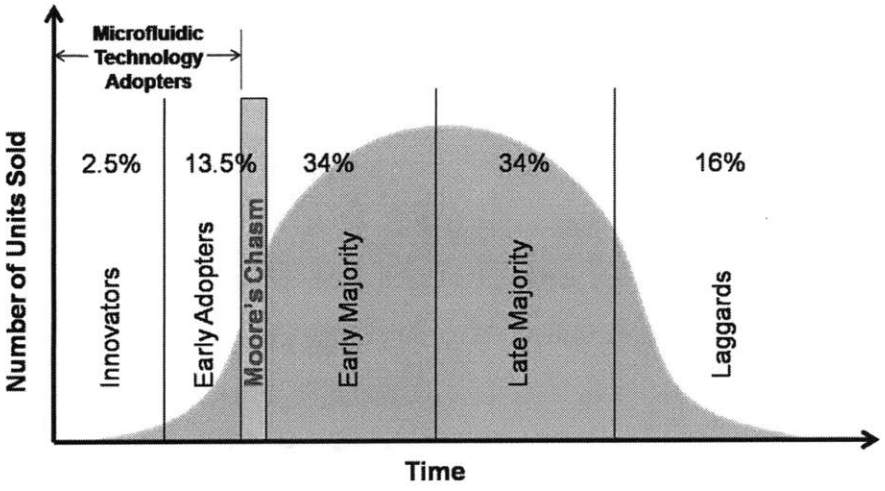

Figure 16. Adoption Distribution Model, Everett Rogers, 1962

In case of microfluidics innovation, innovators are the majority of academic laboratories, which develop and adopt their own microfluidics technologies to launch new research directions or advance current research. They have significant amount of research fund and a dedicated group of scientific staff who extensively collaborate with peers in the field to enable novel science using microfluidics innovations. The innovators are also responsible for launching start-up companies, which develop their research projects for commercial market. For instance, Stephen Quake's laboratory[4] at Stanford University has developed highly scalable and integrated large scale microfluidics integration platform to study novel areas like single cell analysis , chemical synthesis on a chip, proteomic biology and many more. Fluidigm, a start-up company, has developed microfluidics products for commercial market using the innovation from Quake's laboratory. There are several others leading innovators like George Whitesides at Harvard University[5], David Weitz at Harvard University[6], Richard Mathies at University of California Berkeley[7], who are also the opinion leaders in the field.

[4] http://thebigone.stanford.edu/
[5] http://gmwgroup.harvard.edu/
[6] http://www.seas.harvard.edu/weitzlab/
[7] http://chem.berkeley.edu/faculty/mathies/index.php

The early adopters are the research institutes with large budget and highly enthusiastic technology development groups, who are eager to adopt microfluidics innovation to advance their research. They attend conferences, where innovators present their work, and extensively network with the peers to evaluate the specific innovation to adopt. For example, Broad Institute's Genome Sequencing Platform is an early adopter of microfluidics technologies. It has recently adopted RDT 1000 from RainDance Technologies (www.raindancetechnologies.com) to prototype targeted sequencing as a part of its next generation sequencing process improvement efforts. There are early adopters like Stanford Research Institute, Biomedical Diagnostics Institute, Draper Laboratory, NASA Ames Research Center and many others that are adopting microfluidics technologies to advance their research programs.

Based on his work in 1991, (Moore 2002) has identified difficult-to-cross "chasm", which divides five adopters listed above in two distinct groups. The first group is the enthusiasts and visionaries. Almost all the microfluidics adopters fall into the first group. The second group is the pragmatist, which represents the mass market not yet captured by microfluidics. He asserts that crossing the chasm requires the following – *identification and focus on a single target market*, *creating the whole product concept*, *positioning a product among the competition*, *building the market strategy to enter the market* and *penetrating the market widely through distribution channel with the right pricing*. However, this assertion would have to presume that the technology is mature and is ready for adoption since early majority, by definition, waits until the innovation is proved to be successful. The literature survey does, in fact, strongly hint that the technology is immature. At the same time, it supports the previous analysis, which shows that the adoption of microfluidics innovation is only present in the first group – the enthusiasts. Finally, it also reports lack of killer applications or niche market – both of them are market related - as the reasons for the lack of mass adoption.

While Moore's analysis provides insight into important issues for crossing the chasm, it does not provide evidence to ascertain whether the lack of mass adoption is a technology or market related problem. In *Chapter 5,* research data will be used to uncover the exact reason for lack of mass adoption.

4 Business Ecosystem

The state of the microfluidics market is the result of the complex interaction among multiple stakeholders who have different, sometimes unique, needs and interests in microfluidics technologies, products and applications. It is easier to understand this interaction by drawing an analogy from nature. For instance, biological ecosystem is a complex system resulting from the interaction of multiple organisms with their environment. The ecosystem represents competition among organisms for survival and co-evolution of diverse species. It also represents dependency in the form of symbiosis, where the survival of at least one species is dependent on the other.

By using the nature analogy rather nicely, (Moore 1993) defines business ecosystem as *"[a system in which] companies co-evolve capabilities around a new innovation, they work co-operatively and competitively to support new products, satisfy customer needs, and eventually incorporate the next round of innovations*". (Iansiti and Levien 2004) continues this analogy by noting that business ecosystem is, *"[a] loose network of suppliers, distributors, makers of related products or services, technology providers [that] affect, and are affected by, the creation and delivery of a company's own offerings*" .

4.1 Structure of Business Ecosystem

As shown in (Figure 17), the structure of business ecosystem captures the architectural map of the stakeholders – their individual roles and niche areas – and also the flows of financial value and technological innovation. The stakeholders can be broadly grouped into two categories. The first group is the *Users*, who are the beneficiary of microfluidics technological innovation.

The second group is the *Microfluidics players*, which include: spin-off companies, solution companies and original equipment manufacturers (OEM). Microfluidic players are the competitors and complementors. They co-evolve in the business ecosystem to develop innovation into the products for the users.

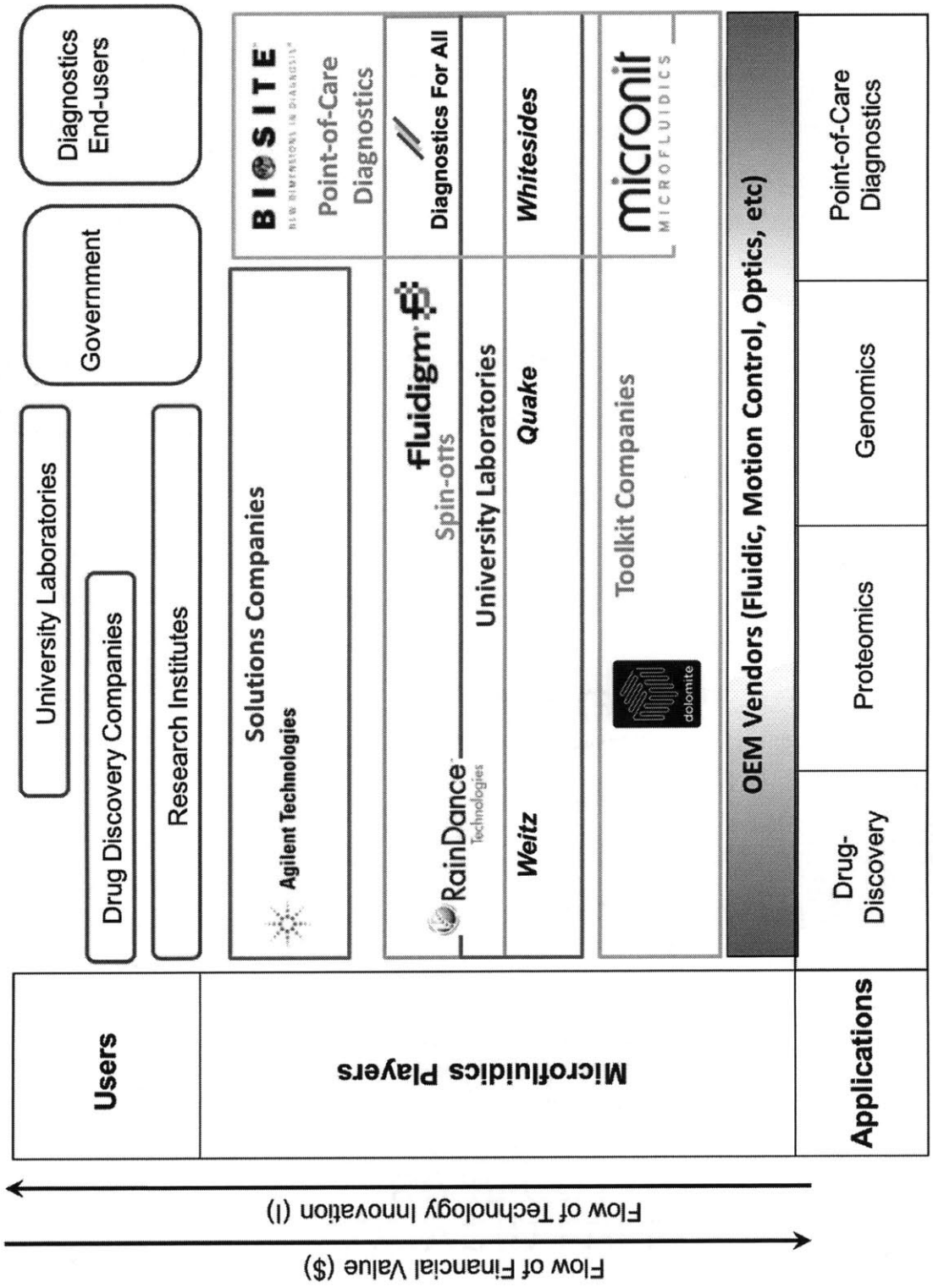

Figure 17. Structure of Business Ecosystem

Original Equipment Manufacturers (OEMs) are the providers of fluidic syringe pumps, motion control systems for liquid handling, electronics and optical systems. The innovation in OEM has enabled precision pumps that deliver highly controlled flow rates with positive feedback, advanced motion control systems with high precision, accuracy and repeatability, and the advanced optics with high-speed CCD camera with optical resolution. As complementors, OEMs provide components to all the other players in the ecosystem.

The *Toolkit Companies* offer microfluidics toolkits – micropumps, micro-valves and custom-designed microfluidic chips for a number of user applications. They provide toolkit directly to the users or other microfluidics players. For example, Dolomite microfluidics offer pumps, valves, connectors, accessories and standard droplet-generator module for droplet based analytical applications. On the other hand, Micronit, in addition to being a toolkit company, is developing products for point-of-care diagnostics and drug delivery.

The *University Laboratories* are the engines for radical microfluidics innovations that offer unique capabilities and enable novel applications not possible before. The breakthrough innovation typically enters the market through the spin-off companies that take the charge of commercializing it. For instance, the droplet merging and sorting capability developed in the David Weitz laboratory at Harvard University was licensed by RainDance Technologies to develop RDT 1000 platform for targeted sequencing for the genomics end-users. But the company has also started collaboration with drug discovery companies for drug screening applications.

The *Solutions Companies*, on the other hand, develop products based on their in-house innovation and microfluidics expertise developed over a long period of time. They source components from OEM vendors but provide specific microfluidics solutions directly to the end-users. For example, Caliper's LabChip system is one of the earliest and most successful microfluidics products for DNA/RNA sizing, separation, quantification and analysis.

Point-of-Care diagnostics (POC) companies develop products to address diagnostic end-users. On one hand, they license technology from university laboratory. For instance, a non-profit

company DiagnosticsForAll (www.dfa.org 2009), has licensed paper microfluidics technologies from Harvard University to develop a simple, easy to use, cheap and disposable diagnostic chip for the developing world. On the other hand, POC companies have also built their own diagnostic products using sourced components from OEM vendors and widely available microfabrication technologies.

4.2 Value Flow Diagram

The value flow in microfluidics business ecosystem is shown in details in value flow diagram (Figure 18). (Crawley 2008) defines value formally as *"Value is delivered when the external process(es) acts on the operand in such a way that the needs of the beneficiary are satisfied at a desirable cost"*. As identified in the previous section, *Users* are the primary beneficiaries but, value flow diagram clearly shows the existence of secondary beneficiaries – *Microfluidics players*. For instance, Toolkit companies, Solution companies, POC companies and Spin-off companies have unique microfluidics component needs, which are fulfilled by OEM Companies. Similarly, Spin-off companies' have unique need for a technology, which is provided by the University Laboratories. This makes the University Laboratories the beneficiaries which also play the dual role of providers. POC companies also play this dual role by supplying diagnostic products to Diagnostics End-users and Government. On the other hand, OEM companies are the only providers which do not receive any benefit from anyone.

The value flow diagram also provides the evidence for the emergence of three major clusters based on two factors – common application(s) of interest and common beneficiaries. *Cluster 1* represents Drug Discovery companies, University Laboratories and Research Institutes, which share common applications – proteomics. *Cluster 2* represents Government and Diagnostic End-users which share common application – Point-of-Care Diagnosis. In addition, *Cluster 2* also includes POC companies for the reason mentioned above. *Cluster 3*, on the other hand, represents *Microfluidics players* like Toolkit, Solution and Spin-off companies, which respectively provide microfluidics components, end-to-end solutions and specialized products to *Users*.

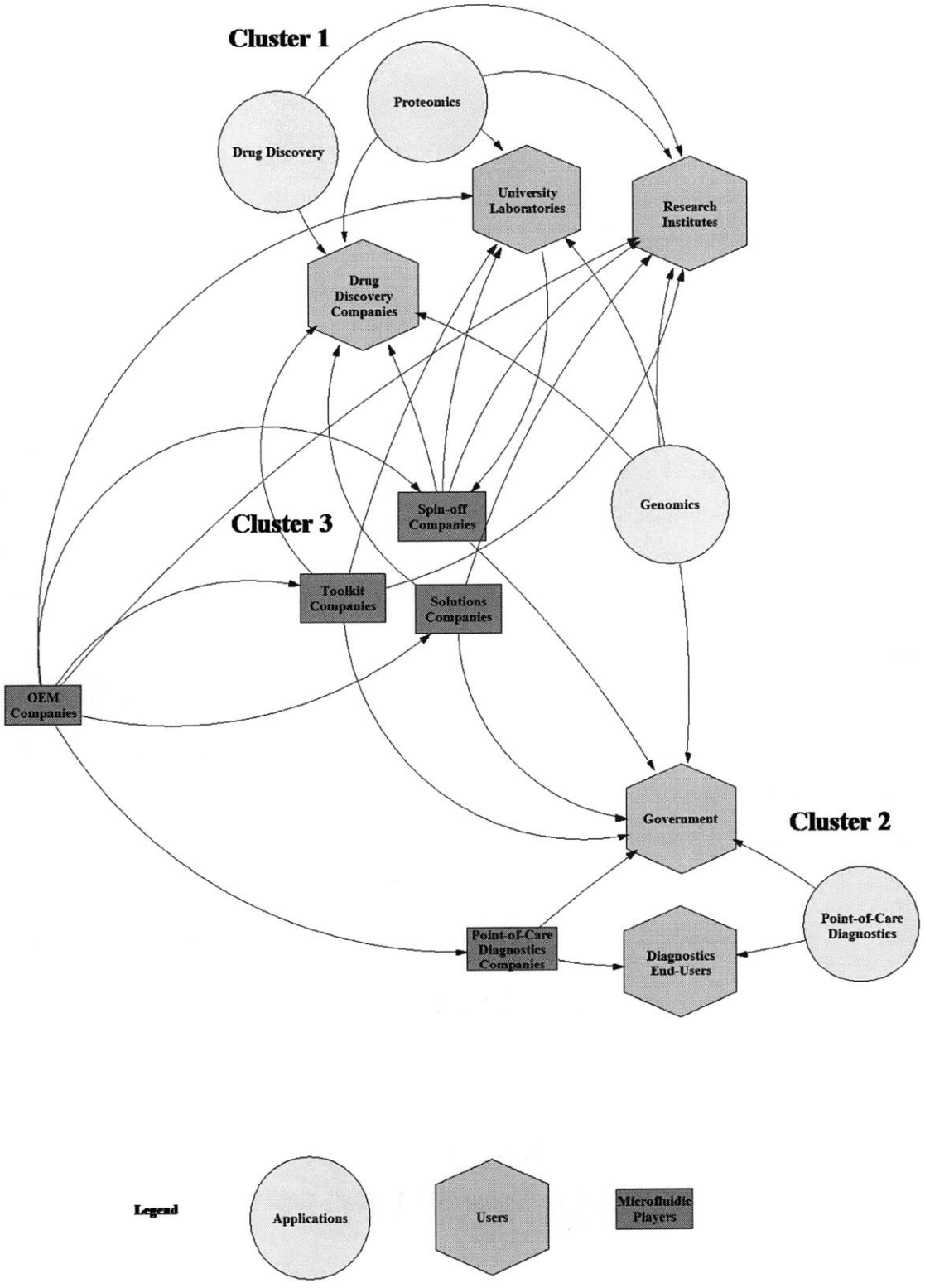

Figure 18. Value Flow Diagram

5 Data Collection and Analysis

The emphasis in the previous chapters has been in the application of analytical frameworks and mental models to the complex evolution of microfluidics ecosystem since its inception during 80s. These chapters helped reduce ambiguity and improve overall understanding of the ecosystem from a qualitative perspective.

To that end, *Chapter 1* provides current state of microfluidics market; *Chapter 2* gives insight into technology innovation, important parameters and key benefits of microfluidics technologies; *Chapter 3* identifies sources of demand generation, lists key customer segments and application areas and, finally explains the diffusion and adoption of microfluidics technologies to this date; *Chapter 4* brings together the microfluidics business ecosystems in terms of relationships and value flow among key stakeholders.

The goal of this chapter is to complement the work done so far – literature reviews and interviews with microfluidics experts with insights from customers themselves. Based on the real-world survey data, the following sections will provide quantitative measure of key benefits, rate of diffusion and adoption, current challenges and future trends in microfluidics. The following sections describe the method used to collect data and offer analysis and interpretation of collected data.

5.1 Research Method and Implementation

The literature review in *Chapter 1* revealed the absence of quantitative analysis of microfluidics market in the current literature. This is because either the data for such analysis has not been collected or is not available in the public domain. As a result, the proposed research method for this thesis includes data collection.

The factors influencing the choice of tool were the following – minimum targeted number of users, even distribution of key user groups and geographical locations of user groups. Based on

this factor, the web-based user group survey was determined to be the best method of collecting data in terms of convenience, cost and time. The free online survey tool offered by (www.surveygizmo.com) was used to design and disseminate the survey to 100 users representing microfluidics innovation and commercialization. The list of users was generated by leveraging personal knowledge of top users, vendors and consultants; personal and professional network in the microfluidics field and finally by looking up the list of attendees at top microfluidics conferences – Miniaturized Systems for Chemistry and Life Sciences (MicroTAS 2008) and Microscale Bioseparations (MBS 2009). The list was carefully prepared to ensure 50-50 distribution between two key user groups – academia and industry.

The survey, which is listed in *Appendix Section*, comprised of a total of 17 questions organized under four main areas – *Participant Background, Technology Parameters, Application* and *Future of Microfluidics*. The survey data was collected between the period of February and July 2009. A total of 41 responses was obtained but only 38 responses were considered based on the completeness of responses. While this number was lower than anticipated, the list of respondents includes some of the top users across important usergroups shaping the microfluidics field today. On the other hand, this number is higher than a minimum necessary in a similar study. Based on the new consumer product development study done by (Griffin and Hauser 1993), which showed that a user group survey is able to capture well over 90% of needs by collecting responses of only 30 customers. With 38 responses obtained during the user group survey, it is presumed that the data holds sufficient information to capture current and future trends for this particular study.

5.2 Data Analysis

The analysis of collected data was done using (Excel 2007). Prior to analysis, the collected data was formatted and organized for clarity and correctness. While the complete responses are listed in *Appendix Section*, the important findings are summarized below.

5.2.1 Participant Background

This section provides information on the background of survey respondents. While the original survey collected user affiliations into four narrow areas – *Academia, Research Institute, Commercial and Other*, for the purpose of the analysis, they are grouped into 2 key user groups in microfluidics – *Academia*, which comprises former two and *Industry*, which comprises the latter two. The respondents are almost evenly split with 58% *Academia* and 42% *Industry* as shown in (Figure 19).

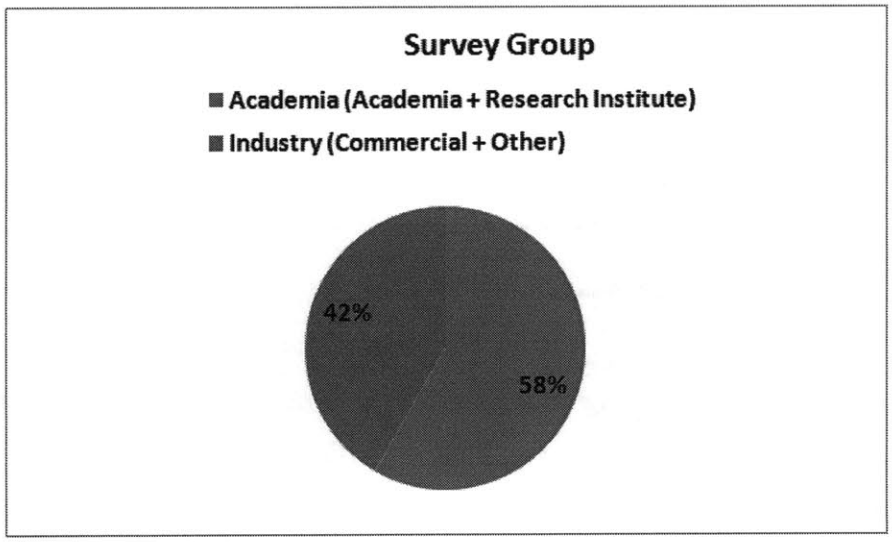

Figure 19. Survey Group

The roles or titles of the respondents are broadly categorized into 4 groups – *Professor, Engineer/Scientist/Researcher, CEO/VP/Director/Manager* and *Student*. As shown in (Figure 20), there is somewhat even split among four categories. But, there is a slight dip in *Professor* category as there is only 17% respondents representing this group. *Engineer/Scientist/Researcher* is the largest group comprising 37% of the respondents as expected. There is equal representation of *Students* and *CEO/VP/Director/Manager* group with 23% each.

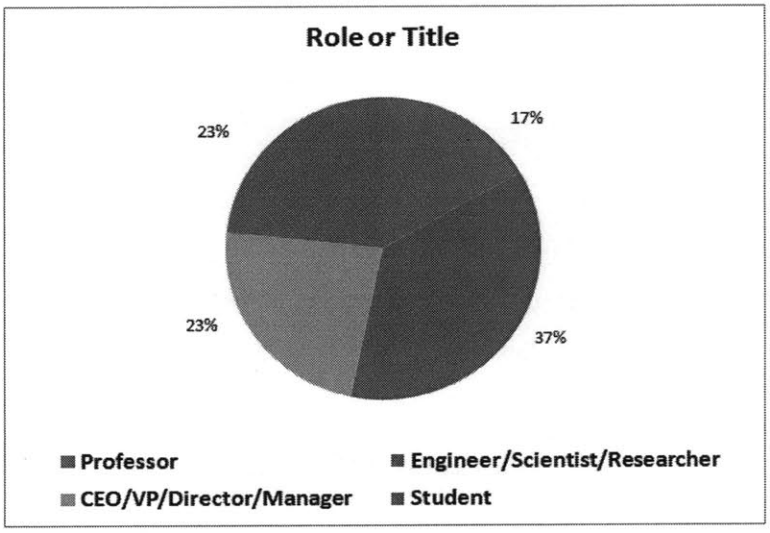

Figure 20. Role or Title

Surprisingly, a significantly large number of respondents (94%), as shown in (Figure 21) have decision-making authority even though it was anticipated that most of the decision-making will be done by *Professor* in *Academia* and *CEO/VP/Director/Manager* in *Industry*. But, this may be because microfluidics is still at early stage of adoption and as such it may be part of the technology exploration efforts by a number of individuals who are the gatekeepers of innovation in an organization.

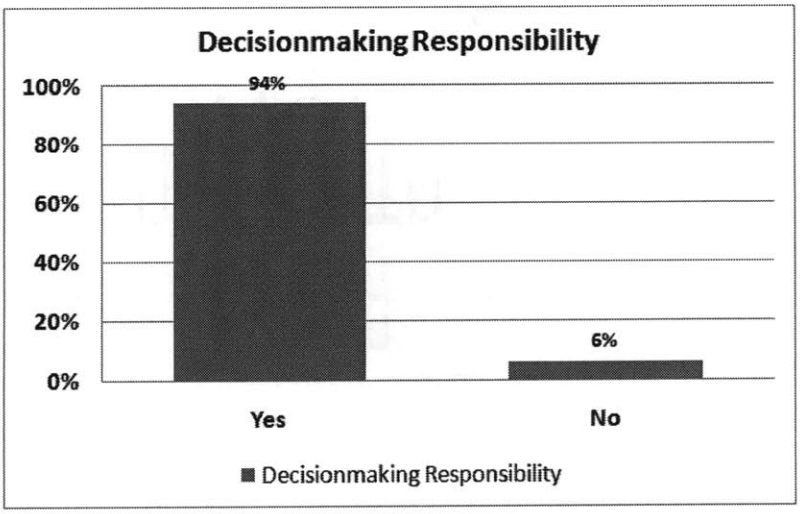

Figure 21. Decision-making Responsibility

There is a vast array of specific microfluidics roles respondents represent. The roles ranges from device fabrication and manufacturing, systems integration to applications specialization in single cell analysis, cell sorting, high-throughput screening and diagnostics. The roles are spread across all application areas – genomics, proteomics, drug discovery and point-of-care diagnostics. The detailed list appears in *Appendix Section* under Survey Response sub-section. In terms of current expertise of respondents with microfluidics , which is shown in (Figure 22), *Work Experience* leads the list with ranking score of 1.6, followed by *Academic literature* (2.1), *Conference/Workshops/Seminars* (2.8), *Other* (3.7) and, finally, *Magazine articles/Newsletters* (3.9). Other includes discussion with fellow colleagues, other researchers in the field or experience with commercial products.

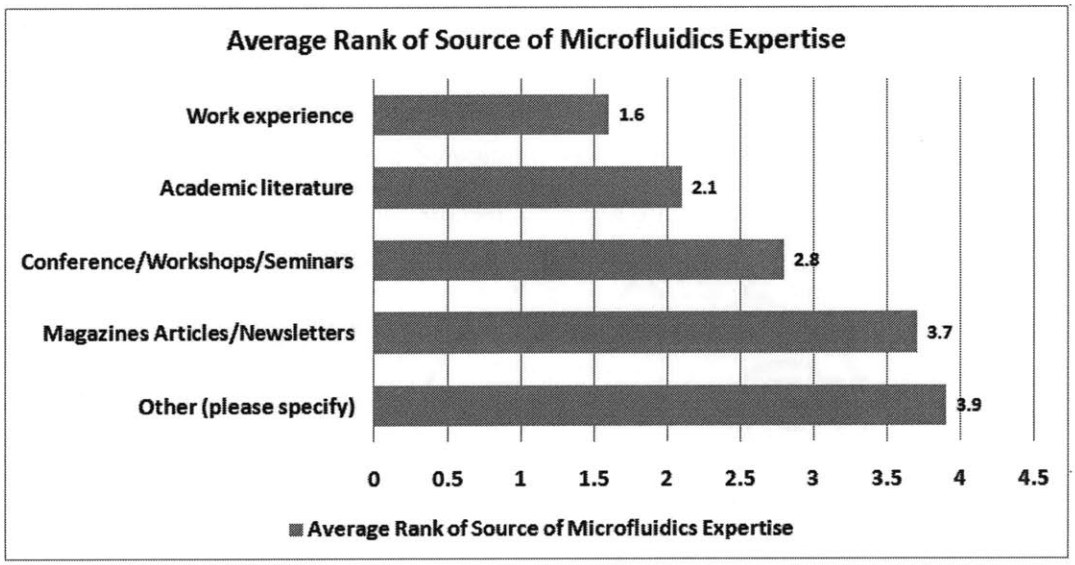

Figure 22. Average Rank of Source of Microfluidics Expertise

5.2.2 Technology Parameters

This section provides detailed information on technology features and important parameters in microfluidics. The survey respondents have diverse experience with microfluidics areas ranging from different manufacturing methods to applications as shown in (Figure 23).

Technology Areas
Soft lithography based fabrication techniques
Injection molding of disposable plastics
Microvalves,, Micropumps, and Routers
Multilayer softlithography/ PDMS chips with pressure-driven flow
Electrokinetics, Capillary effect, gradient formation, pressure driven flows
Droplet Microfluidics
Cell Sorting
DNA Analysis
Polymer chip-based LC, CE, and mass spectrometry
Sensor system for portable target DNA detection

Figure 23. Technology Areas

Microfluidics offers several benefits as described in *Section 2.8 Key Benefits*. As shown in (Figure 24), the *Ranking of Microfluidics Benefits* sheds light on which ones are the most important from the market demand perspective:

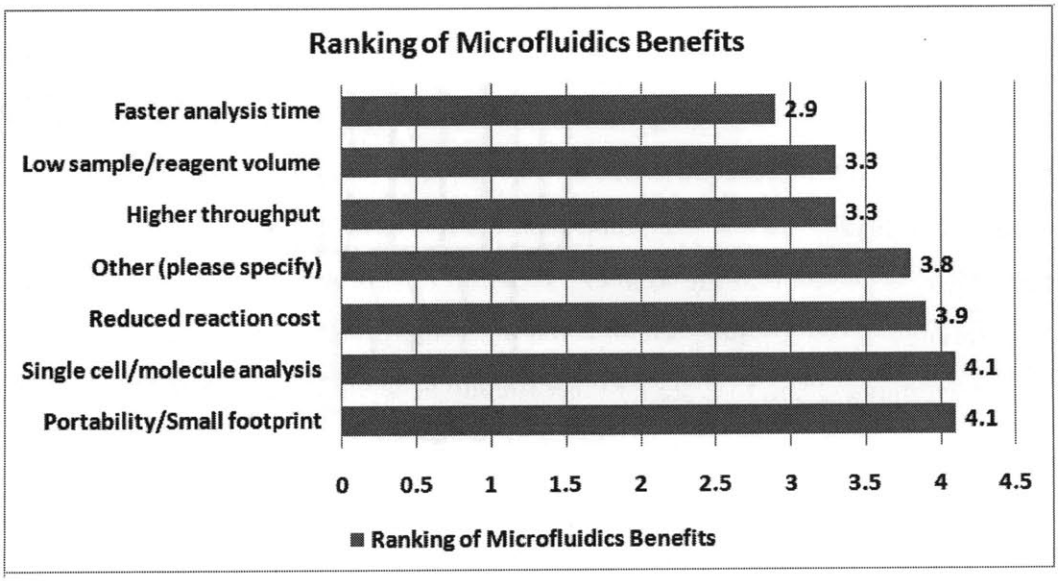

Figure 24. Ranking of Microfluidics Benefits

- *Faster analysis time* leads the rank with score of 2.9. This highlights the continued demand of faster analysis time since the early days of microfluidics. The early

microfluidics products– home diagnostic kits and DNA analysis system – decreased the analysis times compared to the conventional methods. Microfluidics products today offer faster analysis time to decrease cycle time R&D efforts of life sciences end-users.

- The second in the list is *Low sample/Reagent volume* (3.3) and *Higher throughput* (3.3) which receive equal ranking. As the volume of analytical reactions increases, the necessity for lower sample and reagent volume increases too. This is even more critical where the availability of sample is extremely limited (e.g. a tumor sample from a patient). Higher throughput becomes absolutely necessary to keep up with the faster analysis time against the increasing demand of low sample/reagent volume.

- Next on the list are *Other* (3.8) followed by *Reduced reaction cost* (3.9) – lower cost per reaction, which includes both sample/reagent and operational cost. *Other* includes technical features – accuracy and precision, increased resolution and sensitivity, fabrication simplicity and reduced power consumption; and operational features – integration with macrofluidics, low dead volume and simple operation. The fact that technical features did not top the list shows that this ranking represents the needs of the market. And, this is the key takeaway of this ranking. As such, the technical features, even the superior and unique ones like higher resolution, increased sensitivity and single molecule analysis, follow the important market need – faster analysis time (or cycle time). It is expected that the *Reduced reaction cost* be high on the list. But the fact that low sample/reagent volume, which is the most important factor in reaction cost, is second on the list may explain that the cost has already been taken into account.

- Finally, the last on the list is *Portability/Small Footprint* (4.1). This is somewhat surprising because meeting the demand of increased vtolume of reactions would require scaling up conventional solution, which already have bigger footprint. But, additional laboratory space is expensive and may not be easily available. So, the *Small footprint* was expected to be higher on the list. But, this may be due to two reasons. First, the laboratories or companies represented by survey respondents, have easier and cheaper

ways to expanding laboratory space. Second, the respondents think that *Small footprint* alone does not significantly drive the likelihood of adoption by the customers.

The diffusion and adoption of microfluidics technologies is a key topic, whose understanding will shed light current state of both value creation and value capture. The survey provides data to improve such understanding by using responses to rank factors driving interest in microfluidics in respondents' respective organizations as shown in (Figure 25). As it turns out, the top two *Factors Driving Microfluidics Interest* are: *New technology exploration efforts* (91%) and *New application needs* (64%). Both are chosen by more than 50% of the respondents. The data gives insight into the innovation stage of microfluidics technologies. The technology is at early-stage of innovation, driven by academic laboratories and spin-off companies to fulfill the leading edge application needs at both academic laboratories and large research institutes. This conclusion supports the insight obtained using conceptual framework used in *Section 3.4.3 Rate of Adoption.* According to this insight, microfluidics emerged from innovators and thus far has only penetrated the early adopters.

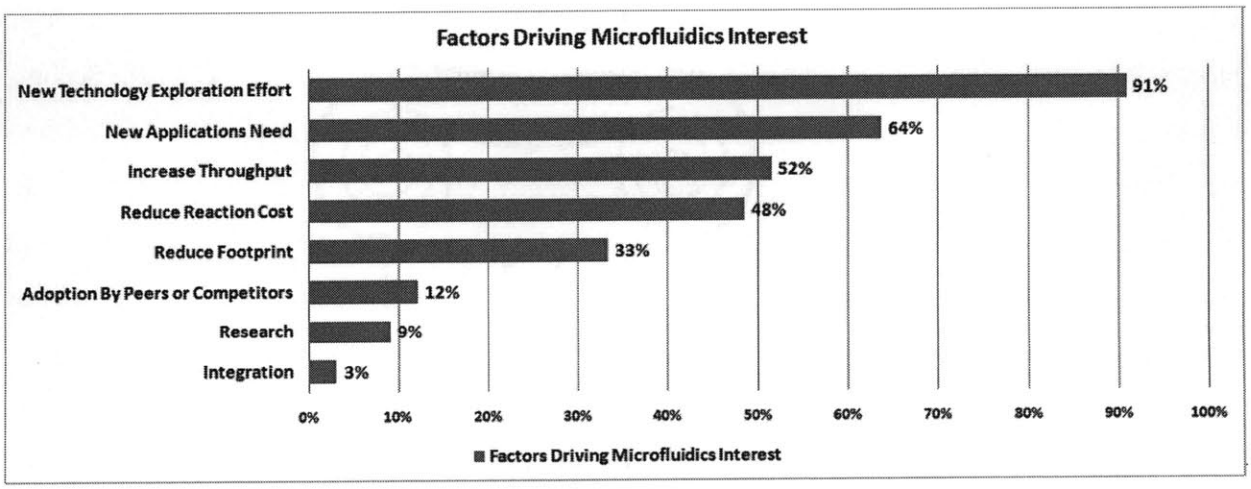

Figure 25. Factors Driving Microfluidics Interest

The next in the list are three factors, which are chosen by more than 25% of the respondents, as follows – *Increase throughput* (52%), *Reduce reaction cost* (48%) and *Reduce footprint* (33%). Again, this is consistent with the analysis done so far. As microfluidics is at early stage of

innovation, the diffusion and adoption is driven primarily by early players – technology explorers and application generators at the academics and research institutes. The needs of the markets influence the ranking of benefits but they are not the primary drivers of diffusion and adoption. Interestingly, while the small footprint was considered the least important benefit, it is considered as one of factors driving interest in microfluidics. Again, this may be because small footprint is a driver of interest among innovators and early adopters, since the miniaturization offer space savings benefit. But from the market perspective, it does not seem to be an important benefit as explained earlier.

5.2.3 Applications

This section captures applications across four major application areas – *Genomics, Proteomics, Drug discovery and Point-of-care-diagnostics*. The respondents have listed an exhaustive range of applications, in each area, which is shown in *Appendix*.

There has been tremendous value creation in microfluidics. The value is shown in two ways. First, it is shown as innovations captured by s-curves (*section 2.7 Technology S-Curve*). Second, it is shown as benefits offered by microfluidics (*section 2.8 Key Benefits*). The survey data shows the value creation as *Impact of Microfluidics Across Areas*. Given the explosion in the incremental and novel genomic needs during the post human genome project era, it is not surprising that *Genomics* was chosen by 33% of respondents as the field with *Large* impact as shown in (Figure 26).

Point-of-Care diagnostics has 31% reporting *Large* impact. This is due to the emergence of new capabilities in molecular diagnostics combined with advantages of microfluidics, which are driving the development in this area.

Drug Discovery has been impacted least by microfluidics, with 63% responses reporting only *Small* impact. *Proteomics* falls in the middle with each 41% responses reporting *Medium* and

Small impact. The impact in *Other* area, which includes chemical testing in environment, also reports *Small* impact of microfluidics.

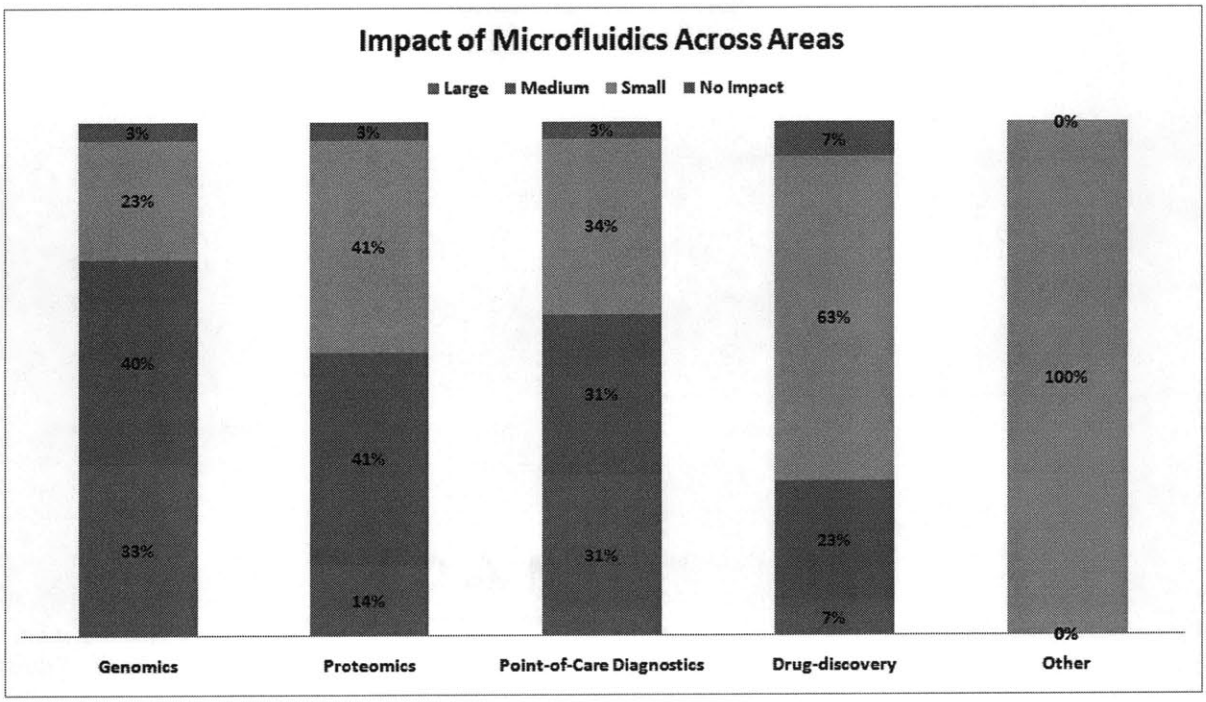

Figure 26. Impact of Microfluidics Across Areas

The impact of microfluidics provides information on the breakthrough research, proof-of-concept experiments and potential adoption. However, the best indicator of actual diffusion and adoption of microfluidics is the adoption of products or services that are championed by the early adopters and/or sold by the commercial companies.. As it turns out, the *Diffusion and Adoption of Microfluidics* has been *Very well* in *Genomics* and *Point-of-care diagnostics*. As shown in (Figure 27), 65% and 53% of responses favor *Very well* or *Somewhat well* in *Genomics* and *Point-of-Care diagnostics* respectively. Again, as expected, the diffusion and adoption has been the least in Drug Discovery and proteomics with 65% and 52% of responses favoring *Not well*. However, there is one important observation to note. Even though one third of respondents chose the *Large* impact of microfluidics in *Genomics* and *Point-of-Care diagnostics*, the percentage of responses reporting *very well* diffusion and adoption of microfluidics, on the contrary, is only 10% and 13% respectively. Why is this so?

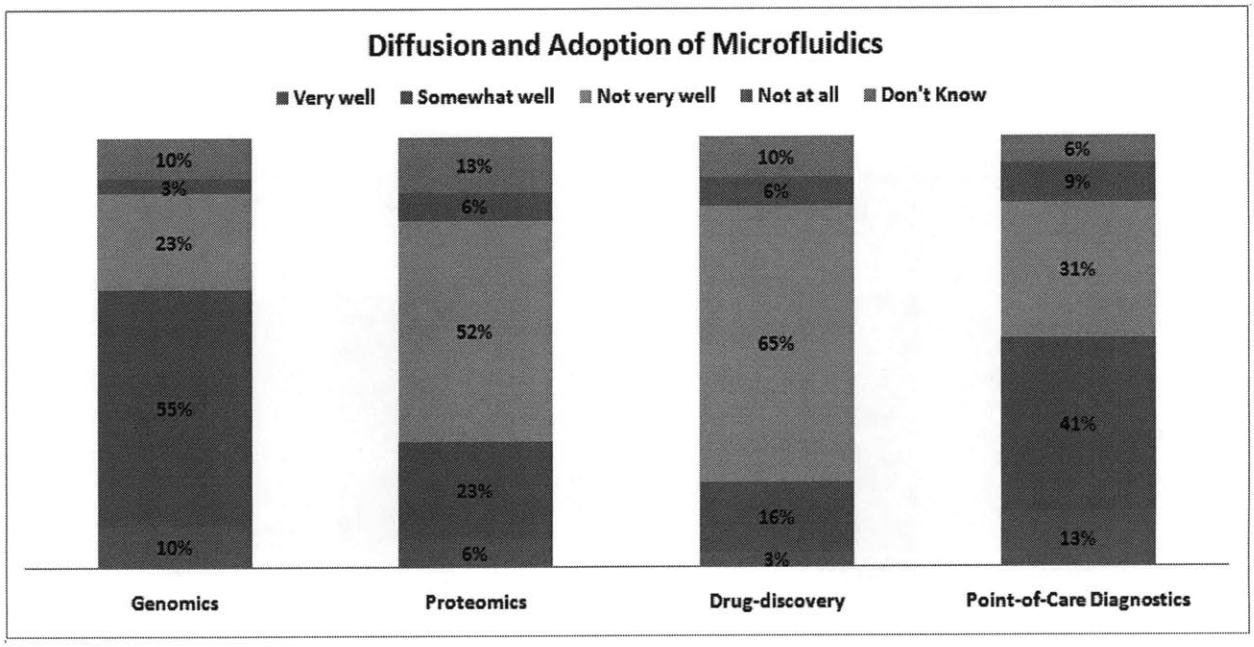

Figure 27. Diffusion and Adoption of Microfluidics

The literature cites absence of killer application or niche market as likely reasons for the lack of commercial success in microfluidics. On the other hand, the data, as shown in (Figure 28) reports *Immature technology*, *Challenges in implementation* and *Adoption resistance* as the top three reasons – with ranking score of 3.0, 3.4 and 3.8 – for the failure of microfluidics benefits capture.

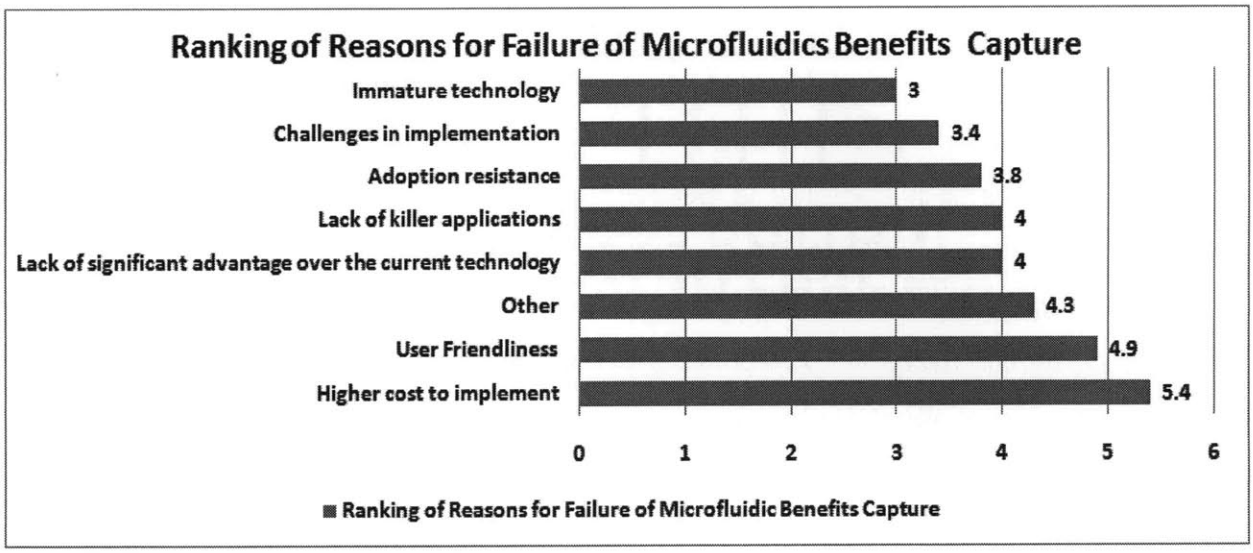

Figure 28. Ranking of Reasons for Failure of Microfluidics Benefits Capture

The data supports the diffusion and adoption framework used in this thesis to show that the technology is primarily in the hands of innovators and early adopters and as such it has not yet crossed the chasm (*Section 3.4.3 Rate of Adoption*). There is a tie between the *Lack of killer application,* a commonly reported reason for failure of microfluidics benefits capture, and the *Lack of significant advantage of current technology* with a score of 4.0. Both of them are ranked fourth. This doesn't support the current belief about the lack of success, which implies that microfluidics need to find the killer application or offer significant advantage (beyond what it offers already) to be successful in the market.

There are other reasons, which include *Other* (platform validation, intellectual property wars and regulatory issues), *User friendliness,* and *Higher cost to implement* with ranking score of 4.3, 4.9 and 5.4. Again, this is line with the lead user framework *(Section 3.2 Customer Segments)*, which describes the innovation and adoption pattern by lead users, who innovate products as users and, as such, user friendliness and cost to implement are insignificant to them compared to that of the mass users.

5.2.4 Future of Microfluidics

Clearly, *Genomics* is driving the adoption of microfluidics. The ranking of microfluidics application in *Genomics* in 10 years are shown in (Figure 29) to highlight specific areas that will shape the future of microfluidics. The sequencing application leads the ranking in the area of capillary electrophoresis sequencing, rapid genome sequencing, genotyping, DNA and RNA analysis and widespread sequencing of personal genomes in the developed world. Point-of-care diagnostics also ranks equally with sequencing application. Next on the list is personalized medicine and viral diagnosis. Finally, the list follows with immunoassays and crime scene investigation application. From the microfluidics perspectives, there is a continued demand for speed, portability, low cost (personal sequencing, point-of-care diagnostics), incremental innovation of current application (capillary electrophoresis based sequencing) and novel applications (viral diagnosis and immunoassays).

Applications	Rank
Capillary electrophoresis based sequencing	1
DNA and RNA analysis	1
Point-of-care diagnostics	1
Research tool for rapid genotyping and genome sequencing	1
Widespread cheap sequencing in developing world	1
Viral diagnosis	2
Personalized medicine	2
Immunoassays	3
Crime scene investigation	3

Figure 29. Ranking Microfluidics Applications in Genomics

While future applications will drive the growth in microfluidics market, the academic players creating new microfluidics technologies or commercial players developing microfluidics products will drive the success of microfluidics technologies. The list of top 10 academic players is shown in (Figure 30). It is clear that Stephen Quake, Stanford (28%), George Whitesides, Harvard (16%), and David Weitz, Harvard (14%) are the top players driving the microfluidics field based on the majority of responses.

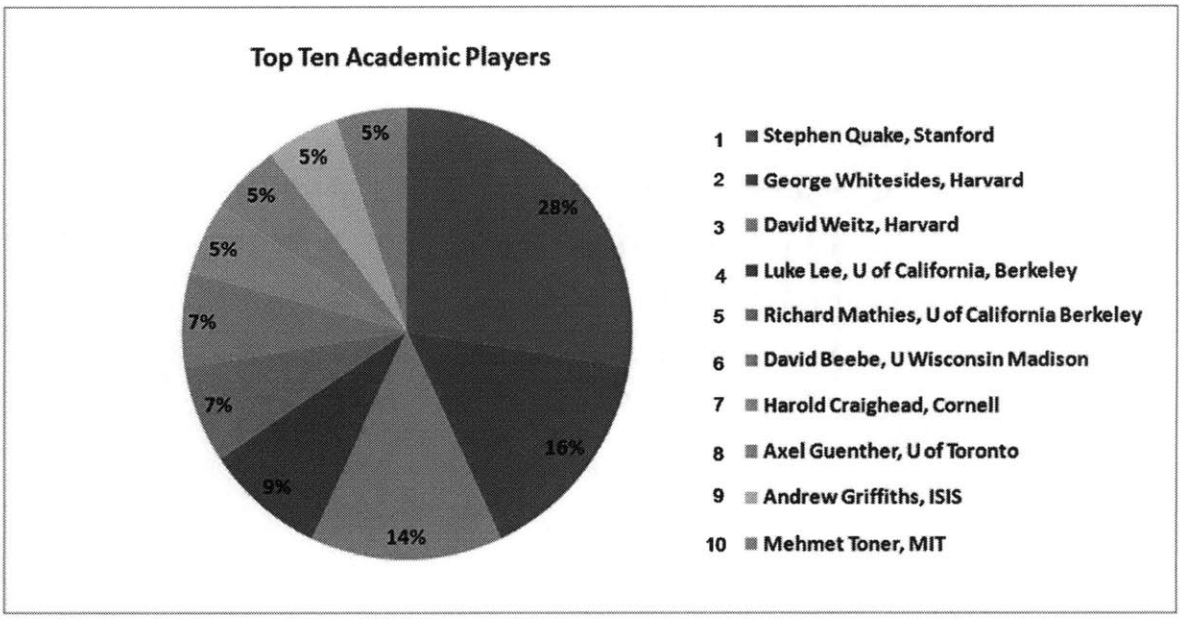

Figure 30. Top Ten Academic Players in Microfluidics

On the other hand, the top 10 commercial players driving the success in microfluidics are shown in (Figure 31). It can be seen that Fludigm (28%), Raindance Technologies (20%), Agilent technologies (formerly Caliper Lifesciences) (13%) lead the list based on the majority of responses.

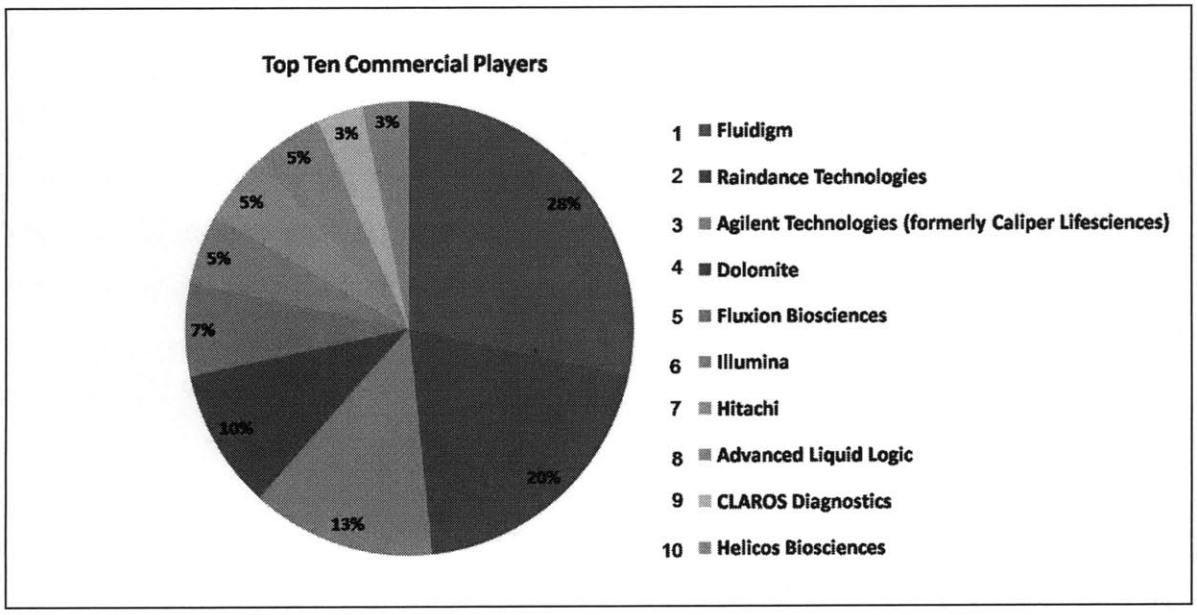

Figure 31. Top Ten Commercial Players

6 Key Findings and Strategic Recommendations

6.1 Key Findings

The analysis in the previous chapter has resulted in the following 5 key findings about the current state of microfluidics market.

i. Microfluidics is at early stage of innovation. Using Moore's adopter distribution model, the diffusion and adoption of microfluidics technologies has been seen so far amongst the innovators and early adopters – the "lead user" of microfluidics technologies. The two major factors driving interest in microfluidics are: *New technology exploration efforts* and *New application needs*. Microfluidics has not yet crossed Moore's chasm and, as such, it has not reached the mass market.

ii. From the market perspective, the top three benefits offered by microfluidics are: *Faster analysis time*, *Low sample/reagent volume* and *Throughput*. Surprisingly, *Portability/ Small Footprint* is the least important benefit.

iii. By using the *Impact* as an indicator of value creation, it was found that most of value creation is in *Genomics* and *Point-of-Care Diagnostics*. It is least in *Drug Discovery*.

iv. By using *Diffusion and adoption* as an indicator of value capture, it was found that there is only limited value capture (in contrast to the amount of value creation) in microfluidics. Almost all of it is in *Genomics* and *Point-of-care of diagnostics*. *Drug Discovery* has seen the least. There seems to be more adoption resistance in *Drug Discovery* than in other application areas.

v. The primary reason for lack of value capture is, surprisingly, technology related. In literature, the most commonly reported reasons were market related – the lack of killer application or niche market. But, thesis reveals that microfluidics has failed to reap the

benefits it offers because it is still an immature technology and, as such, it is still undergoing technology improvement.

Based on these insights and other important findings, the short and long-term strategic recommendations for increasing value capture in microfluidics are developed in the following sections.

6.2 Short-to-Medium Term Strategies

The focus of the short-to-medium term strategies should be on driving the adoption of microfluidics technologies by the end-users. In particular, the companies must focus on the following: improving their specific technologies, addressing challenges in implementation, and re-evaluating their current market strategies to target high demand areas to increase the current rate of adoption. The timeline for implementation of short-to-medium strategies, which are described below, is 1-3 years.

1. Microfluidics is an immature technology, which is still in the hands of innovators and early adopters – top academic laboratories and research institutes – who are also the lead users. Microfluidics companies should build strong collaborations with them on jointly developing products for two reasons:

    a. First, it will give deeper insight into specific technology requirements and product features that appeal most to these lead users. Such insight is critical for building the "right" solutions, which will also appeal to their peers.

    b. Second, it will provide an unparalleled opportunity to test the current applications, using a demo product, for platform validation. As a result, the users will feel confident about switching to microfluidics if there are statistical data available to support the success of a specific application. Such opportunity will further uncover failure modes and specific technical issues that present themselves as

challenges during implementation. By addressing these issues, the product will be ready for the mass market.

2. In general, the market puts higher premium on speed, efficiency and cost rather than the availability of killer application or niche market. Hence, companies developing microfluidics product should emphasize product architecture and design, which enables: *Faster analysis time*, *Low sample/reagent volume* and *Higher throughput*. For instance, *Faster analysis time* can be enabled by a chip design which reduces analyte flow path and the high speed detection optics for capturing the signal. *Low sample/reagent volume* can be enabled by optimized surface chemistry and reaction formulation and high precision analyte delivery (and collection) and re-engineered micro-macrofluidics interface. Similarly, *High-throughput* can be enabled by parallelization in both 2D and 3D by using large scale integration architecture.

   But for specific application like point-of-care diagnostics, *Accuracy* and *Precision* are more important. For instance, there is a more demand for an eight channel microfluidics devices that positively identified H1N1 with a false positive rate of 0.0001% compared to that of a chip that could analyze, say, 1000 patients with a false positive rate of 2%.

3. The largest impact microfluidics has had is in *Genomics* and *Point-of-Care diagnostics*. But, the *Diffusion and adoption* in these areas do not match up with the *Impact*. To drive the *Diffusion and adoption* and, eventually reach the mass market, the companies must develop whole product solutions for high-demand applications, in each area, given below.

   a. *Genomics:* Capillary electrophoresis sequencing; Single molecule sequencing; Rapid sequencing.

   b. *Point-of-Care diagnostics*: Viral diagnosis; Biochemical warfare agent detection; Home health diagnosis.

Furthermore, the companies must focus on a single target application (from the aforementioned list), competitively position and price their products in the market, build the market strategy to enter and identify distribution partners for penetrating the market.

6.3 Long Term Strategies

The focus of the long-term strategies should be on sustaining revenue growth in microfluidics companies. To accomplish this, the companies must focus on the following: developing products for future applications in high growth areas, maintaining strong relationships with early adopters and innovators, and driving the rate of adoption in areas with lower rate of diffusion and adoption. The timeline for implementing long-term strategies, which are described below, is 3-10 years.

1. The companies must re-tool their current products or develop new portfolio of products for applications that are going to be in demand 3-10 years from now. *Genomics* and *Point-of-Care diagnostics* already have the advantage of higher diffusion and adoption relative to *Proteomics* and *Drug Discovery*. As such, the companies must focus on the high-volume applications, some of which may become killer applications or lend themselves to niche market, as given below.

    a. *Genomics:* Low-cost personal sequencing; Personalized medical and diagnostic regimens based upon genetic screening assays.

    b. *Point-of-Care Diagnostics:* Disease diagnosis in developing world; Biomarker detection and quantification.

    As the high-volume applications target the mass market, as opposed to the early adopters, the companies must also focus on features that are important to this group: *User-friendliness*, *Low cost to implement* and *Significant advantage over current technology*.

2. The innovation in *Genomics*, a primary area for microfluidics technologies, is occurring at a rapid pace. As such, companies must maintain strong relationships with innovators and early adopters in this area to: strategically identify new application needs and new product features; and, discover latent needs. The companies must follow how the *Ranking of microfluidics benefits* and the *Factors driving microfluidics interest* are evolving over time. Any change in the ordering inside the lists will have significant impact on the product features and market strategy respectively.

3. The survey data shows significant lack of diffusion and adoption in *Proteomics* and *Drug Discovery* even though there is a long list of applications in each area as shown in *Appendix*. Drug Discovery, in particular, is ripe for infusion of microfluidics given current inefficiency and high cost in bringing a single drug to market. In fact, the current trend in drug discovery is alarming. The billion dollar drugs are coming off patent while, at the same time, number of new drugs in the market has been declining in recent years. With its benefits of *Faster analysis time*, *Low sample/reagent volume* and *Scalability*, microfluidics is well-positioned to meet the drug-discovery needs.

   However, *Adoption resistance* is the primary cause in the latter due to financial challenges during implementation. For instance, pharmaceutical companies require validation of microfluidics technologies before they can be implemented. However, they are unwilling to pay for the validation of microfluidics platforms. The companies may consider two strategies to address this challenge.

   a. First, is to change business strategy to focus on non drug-discovery market until the economy recovers. As economy show strong signs, this will encourage investment from companies into new tools. However, this may not be easy one for a company that has made significant capital and intellectual property investment in developing technologies for drug discovery market.

   b. Second, is to consider governmental grants for in-house validation and collaborate with pharmaceutical companies only on using their biomarkers/reagents.

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Appendix

I. Survey Questions and Responses (www.surveygizmo.com)

1.I.1 Participant Background

1. Which one of the following are you affiliated with? Please pick as many as applicable.

Academia	Research Institute	Commercial	Other
Bioengineering	Biomedical Diagnostics Institute	Biotech	Government
Soft Lithography	BioMEMS Resource Center	Life Sciences Tools Company	Chemical Sensor Development
Analytical Instrumentation	Genomics	Microfluidics	Independent Consultant
Biological Microtechnology and BioMEMS		Biotechnology	Independent Consultant
California State University, Los Angeles		Chemical & Life sciences Measurement Instrumentation	
Drexel University, Philadelphia PA		Instrument and chip manufacturer	
Lab on Chip Technology		Manufacturing	
Microfluidic biomedical devices, microfluidic devices for HTS (high-throughput screening)		Microfluidic device design	
Microfluidics and Biosensors		Microfluidic Diagnostics	
Microfluidics, DNA analysis, Lab on a Chip		Tool developer for life sciences	
Micromanufacturing, General		Medical Devices	
Microsystems		Microsystem Technology	
Multiple biosensing, Surface modification, Fluid handling			
Nanobiotechnology			

Nanofluidics & Microfluidics
Stanford
Systems Biology
UC Berkeley

Total Response	Counts	Percentage
Academia	18	50%
Research Institute	3	8%
Commercial	11	31%
Other	4	11%
Total	**36**	**100%**

Group	Counts	Percentage
Academia (Academia + Research Institute)	21	58%
Industry (Commercial + Other)	15	42%
Total	**36**	**100%**

2. What is your role or title?

Professor	Engineer/Scientist/ Researcher	CEO/VP/Director/ Manager	Student
Assistant Professor	Postdoctoral Researcher	VP of R&D	Doctoral Candidate
Professor	Integration Engineer	Associate Professor and Chief Technology Officer	Graduate Student
Associate Professor	Postdoctoral Fellow	Bio-Automation Manager	Ph D Student
Asst. Professor	Principal Engineer	CEO	PhD candidate
Professor of Chemistry	Project Scientist	Commercial Director	PhD Candidate (Researcher)
	Research Fellow	Director	PhD Researcher
	Senior Engineer	Independent Consultant	PhD student
	Senior Scientist		
	Senior Research Scientist		
	Visiting Fellow		
	Research Assistant		

Total Response	Counts	Percentage
Professor	5	17%
Engineer/Scientist /Researcher	11	37%
CEO/VP/Director/ Manager	7	23%
Student	7	23%
Total	**30**	**100%**

3. Do you make decisions regarding microfluidics technologies in your company?

( ) Yes
( ) No
( ) Not Sure

Response	Count	Percent %
Yes	34	94%
No	4	6%
Total	**38**	**100%**

4. What is your role in regards to microfluidics field? Please list as many as applicable.

Role
Biomedical Devices
Consultant
Developing applications for genomics, immunoassays, and cell-based assays
Device and system development, cell culture and assays
Droplet microfluidics, single cell applications, protein and nucleic acids analysis
Droplet-based microfluidic solution for sequence selection.
Emulsion PCR for sequencing
Microfluidic biomedical devices, microfluidic devices for HTS (high-throughput screening)
Soft lithography
We develop new technologies as needed to integrate into our systems
We use microfluidic devices to make our droplet primer libraries.
Agilent Technologies
Bioanalysis and separation
Biomarker detection
Biosensor development
Cell analysis using microfluidics
Cell sorting

Chemical & life science measurement
Chemical Sensor Development
1. Chips; pumps; software; technology; IP
Continuous flow microspotter
Design and manufacturing of plastic chips
Developer of new microfluidic devices
Developing microfluidics instruments for biological testing
Developing single cell analysis
Development of new microfluidics technologies and applications.
DNA analysis, protein microarrays, bacteria detection, etc
Electrokinetics; Clinical & point-of-care diagnostics; Sample preparation
Evaluating various technologies
Finished products using microfluidics
Fluidic chip design
HPLC & CE
I design and fabricate microfluidic devices for biological experiments.
I sometimes purchase pre-fabricated microfluidic chips for biological assays.
I use some off-the-shelf components such as Nanoports (from UpChurch Scientific)
Integrated Diagnostics systems
Integration engineer: we integrate existing and novel technologies to make functional, useful systems
Microfluidic lab and test equipment
Microfluidic device design and manufacturing
microfluidic technology
Microfluidics technologies development and fabrication
Molecular cell biology
Multi-layer soft lithography designer.
2. My thesis involves building novel microfluidic components and the manipulation of fluids with electric fields
Non-conventional microfluidic materials (ceramics, metals)
Point-of-care diagnostics
Use some microfluidics-based instrumentation from industry.
We are using commercially available components
We use technologies already developed to integrate into our systems
We use technologies already developed to integrate into our systems. We integrate existing and novel technologies to make functional, useful systems

5. Please rank your source of current expertise in microfluidics.

Value	1	2	3	4	5	Average Rank of Source of Microfluidics Expertise
Other (please specify)	1	1	1		5	**3.9**
Magazines Articles/Newsletters	1	2	3	27	1	**3.7**
Conference/Workshops/Seminars	2	9	22	3	1	**2.8**
Academic literature	6	19	9	1		**2.1**
Work experience	26	6	2	3	1	**1.6**
Total Respondents	**38**					

6. If you selected "other" as your area of expertise in previous question, please specify in the box below.

Other	Number	Percentage
Commercial products	1	25%
Consultation with colleagues in the field	1	25%
Discussion with other researchers	2	50%
Total Respondents	4	100%

1.I.2 Technology Parameters

7. Please list specific microfluidic technology you are using to respond to this survey. If your responses apply to general area of microfluidics, please leave it blank.

Please refer to Figure 23

8. Please rank the following important benefits of specific microfluidic technology you have experience with.

Value	1	2	3	4	5	6	7	Average Rank
Portability/Small footprint	5	5	2	9	4	10	2	**4.1**
Single cell/molecule analysis	8	3	2	5	4	6	6	**4.1**
Reduced reaction cost	3	5	6	8	6	6	1	**3.9**
Other (please specify)	4		1	2	1	2	2	**3.8**
Higher throughput	6	10	4	4	7	3	1	**3.3**
Low sample/reagent volume	4	7	13	5	6	3		**3.3**
Faster analysis time	8	7	10	4	6	1		**2.9**
Total Respondents 38								

9. If you selected "other" benefit in the previous question, please specify in the box below.

Other
Fabrication Simplicity
Integration with macrofluidics
Low Dead Volume
New Capabilities Impossible at Larger dimensions
Performance Enhancement: Resolution & Sensitivity
Reduced Power Consumption (pumping etc.)
Simple Operation (minimal control instrumentation)
Stand Alone systems

10. What factors are driving yours or your company's interest in microfluidics?

Value	Count	Percentage
Integration	1	3%
Research	3	9%
Adoption By Peers or Competitors	4	12%
Reduce Footprint	11	33%
Reduce Reaction Cost	16	48%
Increase Throughput	17	52%
New Applications Need	21	64%
New Technology Exploration Effort	30	91%
Total Responses	**103**	
Total Respondents	**37**	

1.I.3 Applications

11. In your opinion, what are some of the most important applications in each category below.

Genomics
Capillary electrophoresis based sequencing
Low-cost sequencing of individual genomes
Rapid sequencing
Emulsion PCR for sequencing
Research tool for rapid genome sequencing or genotyping
Single molecule sequencing
Sequence selection
Organism identification, SNP/RNA
DNA and RNA analysis
High-throughput analysis

Low copy numbers
Low cost separation/analysis
HTS of patient genes or populations for mutations in cancer
Fluids manipulation for sequencing equipment
Small reaction volumes, Higher efficiency reactions
Personalized medical and diagnostic regimens based upon genetic screening assays
Crime scene investigation/DNA fingerprinting
Portable DNA analyzer
Cancer diagnostics, Molecular diagnostics
Custom microarrays
Sample handling

Proteomics
Diagnostics
Personalized medicine
Discovery and implementation of protein crystallization conditions
Electrophoresis; Anti-body based screening; Coupled MS
HTS of in vitro synthesized target proteins as tools for the pharma industry
Elucidation of proteins involved in cancer oncogenesis
Immunoassays
Biomarker and discovery, protein detection
Biomarker screening
Continuous high throughput separation/ sample prep
Immnuoassays
Microarrays, sample handling, binding reactions
Pre-symptomatic disease detection
Protein analysis
Protein crystallography
Protein ID, QA/QC
Protein microarrays
Protein structure determination
Sensors, high-resolution separations
Small reagents
Targeted proteomics

Point-of-Care Diagnostics
Viral diagnosis
Bio/chemical warfare agent detection
Developing world disease diagnostics - HIV, Tuberculosis (strain specific for drug resistance), Malaria
High speed diagnostics, global health

Biomarker detection and quantification
Metabolic Disorders, Chronic conditions, Monitoring disease
Real-time rapid assays for use in surgical arenas
Self contained disposable and low cost lab-on-chip
Analysis of blood- disease detection and monitoring
Biomarker identification
Blood analysis
Molecular diagnostics
Distributed diagnostic systems for healthcare and environmental monitoring
Drug compatibility & metabolism, disease detection
Glucose detection
Health care for developing countries
Home made diagnostics
Integrated sample preparation
Low cost, high accuracy
Most important when applied in the clinical setting
Portable multiplexed assays
PSA testing
Quick safe tests for wide range of conditions
Rapid bedside diagnostics, Portable Field diagnostics

Drug-discovery
High throughput screening
High throughput, Cell-based assays, Tox, Biodistribution
Personalized medicine
Single cell screening; primary cell screening
Tissue platforms for drug toxicity
Combinatorial synthesis of new drugs
Compound synthesis and purification
Developing new drugs and targets for complex diseases, such as HIV
High-throughput studies
High content screening
High throughput reaction monitoring
High-throughput analysis of millions of drugs and combinations
High-throughput screening
Ion channel assays
Miniaturization of analytical instruments
Rational drug design
Tools for large scale screening of drugs on organ-specific tissues
Toxicity testing
Validation efforts

Other
Chemical warfare agent detection and related technologies
Chemical, environmental rapid testing
Low cost, field-deployable miniaturized chemical sensors for environmental monitoring

12. In 10 years from now, how would you rank the genomics application you have listed in the previous question?

Applications	Rank
Capillary electrophoresis based sequencing	1
DNA and RNA analysis	1
Point-of-care diagnostics	1
Research tool for rapid genotyping and genome sequencing	1
Widespread cheap sequencing in developing world	1
Viral diagnosis	2
Personalized medicine	2
Immunoassays	3
Crime scene investigation	3

13. How large has been the impact of microfluidics across other areas?

Area	Large	Medium	Small	No Impact
Genomics	33%	40%	23%	3%
Proteomics	14%	41%	41%	3%
Point-of-Care Diagnostics	31%	31%	34%	3%
Drug-discovery	7%	23%	63%	7%
Other	0%	0%	100%	0%
Total Respondents	**32**			

14. If you selected "other" in previous question, please list in the box below.

Chemical environmental testing

15. How well do you think the rate of diffusion and adoption of microfluidic technology has been since early 90s?

Area	Very well	Somewhat well	Not very well	Not at all	Don't Know
Genomics	10%	55%	23%	3%	10%
Proteomics	6%	23%	52%	6%	13%
Drug-discovery	3%	16%	65%	6%	10%
Point-of-Care Diagnostics	13%	41%	31%	9%	6%
Total Respondents	**32**				

16. Please rank the following reasons for failure, if any, in capture of benefits of microfluidic technologies.

Value	1	2	3	4	5	6	7	8	Average Rank
Higher cost to implement	1	1	2	3	2	8	8		**5.4**
User Friendliness	1	3	1	5	4	6	6		**4.9**
Other	3	1		1				3	**4.3**
Lack of significant advantage over the current technology	2	4	5	8	6	2	2	1	**4**
Lack of killer applications	6	4	1	8	1	2	2	4	**4**
Adoption resistance	3	6	8	2	3	4	3	1	**3.8**
Challenges in implementation	6	5	8	2	7	3		1	**3.4**
Immature technology	7	8	7	2	2	1	2	1	**3**
Total Respondents	**33**								

17. If you selected "other" in the previous question, please list in the box below.

Other
High investment to transition from R&D to product
IP wars, Patents, making access expensive
Regulatory issues

1.I.4 Future of Microfluidics

18. Please list top commercial players, in your opinion, which are most likely to drive success in the microfluidics field.

Commercial Players	Percentage	Count
Fluidigm	16%	17
Raindance Technologies	11%	12
Caliper Life Sciences	10%	11

Agilent Technologies	8%	8
Dolomite	6%	6
Fluxion Biosciences	4%	4
Illumina	3%	3
Hitachi	3%	3
Advanced Liquid Logic	3%	3
CLAROS Diagnostics	2%	2
Helicos Biosciences	2%	2
Microchip Biotechnologies	2%	2
Biorad	2%	2
Roche	2%	2
Micronics	2%	2
Gyros	2%	2
Micronit	2%	2
MF 3	1%	1
Corning	1%	1
Established diagnostics cos.	1%	1
Life Technologies	1%	1
Stokes Bio	1%	1
454 Life Sciences	1%	1
Applied Biosystems	1%	1
Axis Shield	1%	1
Bayer	1%	1
Biotrove	1%	1
Phillips	1%	1
Picovitro	1%	1
Quorum Technologies	1%	1
Biorad	1%	1
BD	1%	1
CellASIC	1%	1
Eksigent	1%	1
Sandia Labs	1%	1
Spin X	1%	1
Upchurch Scientific	1%	1
Wasatch Microfluidics	1%	1
Affymetrix	1%	1
Nano-Terra	1%	1
Total	**100%**	**106**

19. Please list top academic players, in your opinion, that are most likely to drive success in the microfluidics field.

Academic Players	Percentage	Count
Stephen Quake, Stanford	16%	16
George Whitesides, Harvard	9%	9
David Weitz, Harvard	8%	8
Luke Lee, U of California, Berkeley	5%	5
Richard Mathies, U of California Berkeley	4%	4
David Beebe, U Wisconsin Madison	4%	4
Harold Craighead, Cornell	3%	3
Axel Guenther, U of Toronto	3%	3
Andrew Griffiths, ISIS	3%	3
Mehmet Toner, MIT	3%	3
Sam Sia, Columbia	3%	3
Andreas Manz, FRIAS	3%	3
Paul Yager, Washington U	3%	3
Rustem Ismagilov, U Chicago	2%	2
Abe Lee, U of California, Irvine	2%	2
Juan Santiago, Stanford	2%	2
Michael Ramsey, U of North Carolina	2%	2
John Wickswo, Vanderbilt	2%	2
Aaron Wheeler, U of Toronto	2%	2
KTH	1%	1
Jensen Klavs, MIT	1%	1
Todd Thorsen	1%	1
Fraunhof Institute	1%	1
Jonathan Sweedler, U of Illinois UC	1%	1
James Landers, U of Virginia	1%	1
Bruce Gale, U of Utah	1%	1
Karlsruhe University	1%	1
Scripps Institute	1%	1
IMM	1%	1
Marc Madou, U of California, Irvine	1%	1
Michel Maharbiz, U of California, Berkeley	1%	1
VTT	1%	1
Frank A. Gomez, CSU, Los Angeles	1%	1
Patrick Doyle, MIT	1%	1
University of Strasbourg (ISIS)	1%	1
Charles Henry, Colorado State U	1%	1
Mehmet Yanik, MIT	1%	1
Ronald W. Davis, Stanford	1%	1
University of California LA	1%	1
Joel Voldman, MIT	1%	1
Susan Lunte, U of Kansas	1%	1
University of Tokyo	1%	1

Sangeeta Bhatia, MIT	1%	1
University of Chicago	1%	1
Total	**100%**	**104**

20. Please state your name and/or affiliation (Optional)