Knowledge Transfer and the Limits to Profitability: An Empirical Study of Problem-Solving Practices in Semiconductor Manufacturing and Process Development

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***Abstract*—A broadly based empirical study of problem-solving practices in the semiconductor industry reveals that the inability to transfer knowledge rapidly is limiting the profitability of semiconductor manufacturers. Extremely high user loss rates force users and suppliers of semiconductor process and diagnostic technology to solve problems as rapidly as possible. Unfortunately, both sides possess knowledge that is required to solve problems but cannot be transferred rapidly enough for extensive losses to be avoided. Collaboration between users and suppliers, in which problem solvers physically relocate from one side's site to the other's, is minimizing losses but creating a shortage of experts that threatens the health of the industry. A series of practices that will reduce the cost of knowledge transfer is presented. Foremost among these is the establishment of an Internet-enabled toolkit for remote diagnostics and repair.**

***Index Terms*—Development, knowledge, problem, limits, manufacturing, process, profitability, semiconductor, solving, transfer.**

I. Introduction

SEMICONDUCTOR manufacturers make investments in R&D and plant equipment that can run in the billions of dollars, and these enormous outlays need to be recovered in a relatively short period of time [1]. Semiconductor manufacturers try to amortize their investments by elevating their yields to profitable levels as rapidly as possible [2] and by subsequently optimizing capital productivity [3]. Problems related to yield and capital productivity can induce loss rates exceeding $10 000 per minute [4], [5], which are unsustainable in the long run. Thus a sense of urgency characterizes problem solving in the semiconductor industry, and the ability to solve problems rapidly has become a major source of competitive advantage for semiconductor manufacturers.

In this paper, I investigate how the semiconductor industry solves problems related to manufacturing and process development. In Section II, I identify factors that could affect the nature of problem solving, and I state hypotheses that would be confirmed if each of these factors were to drive problem solving in semiconductor manufacturing and process development. In Section III, I discuss the research methods and variables that I use to test the hypotheses from Section II. In Section IV, I present the results of the study. I discuss their implications in Section V and make recommendations in Section VI.

II. Factors That Affect Problem Solving

In general, agency decisions related to problem-solving activity are the prerogative of the problem owner. He/she determines who engages in specific problem-solving activities and where these problem-solving activities are to occur. The problem owner has the option of letting an internal or external actor engage in problem-solving activity, and the problem owner can also, in principle, determine the locus of problem-solving activity.

In semiconductor manufacturing and process development, the user of semiconductor process and diagnostic technology tends to be the problem owner, and in the overwhelming majority of cases in this study, the chipmaker is the user (and owner) of process and diagnostic technology. As the owner of a problem, the chipmaker essentially has three options with respect to agency choice: 1) he/she can select an internal actor; 2) he can request the supplier of the allegedly faulty technology to engage in problem-solving activities; 3) he can ask a third party to conduct said activity; or he/she can attempt various combinations of 1), 2), and 3). The chipmaker also influences the locus of problem solving, which can occur at the user (chipmaker) site, at the supplier site, or at the site of the third party.

The chipmaker has a strong incentive to come up with an adequate solution to the problem as rapidly as possible. The cost of the fix should be less important than the speed of the fix. As a result, the chipmaker is likely to choose the actor and the locus of problem solving that he/she believes will yield an adequate solution to the problem in the shortest amount of time. His/her agency decisions may thus be influenced by the following factors.

Specialization. Research into the nature of problem solving [6] suggests it to consist of trial-and-error procedures that are guided by some insight as to the direction in which a solution might lie. This insight is likely to reside in the mind of a problem solver that possesses expertise in related matters [7] that he/she has accumulated through experience. It is, thus, in a semiconductor manufacturer's interest to let the specialist with the most experience in solving problems of a specific type solve

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a problem of that type, because the insight gained by experience enables the specialist to solve the problem more rapidly. For example, an equipment engineer with years of experience in vacuum systems would be considered a specialist or first best expert in this field. He/she is more likely to solve a problem that is related to vacuum systems more rapidly than, say, a lithography engineer is. The vacuum expert would make fewer errors and thus require fewer trials than the lithographer would. It is thus more efficient for the vacuum systems engineer to solve problems related to vacuum systems.

If the problem owner makes his/her agency decisions solely based upon who is the first best expert, then the problem owner should let suppliers of technology diagnose and repair the systems they supply from the site they supply. In that case, the following hypothesis should be confirmed.

H1: *The supplier of technology conducts problem-solving activity at the supplier site.*

The suppliers of a technology are specialists in the technology that they supply, and they have the most experience solving problems related to that technology. For example, a leading supplier of medical diagnostic tools has set up communication links to every unit in the field, which allows him/her to solve problems remotely from one centralized site. This practice is much more efficient than having technicians employed by a hospital solve technical problems on a medical instrument. The hospital technicians would have to sustain various instruments of different types, whereas a centrally located specialist would be in charge of multiple units of the same type.

Coordination costs are overhead costs that a company incurs when it engages in problem solving activity. They include the cost of writing a contract with an external actor or the costs of moving a problem solver—be he/she an internal employee or an external actor—to the locus of problem solving. In the semiconductor industry, which generally operates under time pressure, coordination costs typically manifest themselves in the form of delays. A manager in charge of technology integration in a semiconductor R&D facility explains.

> "We have very experienced equipment people, and so does the supplier, but by the time the supplier gets its crew here, we may have already fixed the problem."

If semiconductor manufacturers were to make their agency decisions purely on the basis of coordination costs, then they would hire all their problem-solvers and let them solve problems at their own site. All other things being equal, internal actors acting locally will deliver the solution with the lowest coordination costs, because they essentially eliminate the need for potentially time consuming activities such as travel and contract negotiations. Under these conditions the following hypothesis should be confirmed.

H2: *The chipmaker conducts problem-solving activity at the chipmaker's site.*

"***Sticky Information***" is defined as information (or knowledge) that is extremely expensive to generate, acquire or transfer [8]. Sticky information can exist in the form of tacit knowledge, which is embodied in individuals and difficult to document, encode or articulate [9]. A user (supplier) of technology may also acquire confidential information from a supplier (user). This information is sticky because the user (supplier) is not allowed to pass it on to another supplier (user). Finally, information required to solve a problem can be embodied in specific pieces of equipment or specific sites, which requires the problem-solver to relocate to the specific equipment or site when he/she engages in problem-solving activity.

The user and the supplier of a technology can possess different items of sticky information that need to be brought together at one locus in order to solve a problem. For example, a representative of a supplier firm can possess tacit knowledge related to fixing a piece of equipment that the supplier makes, but he/she is unable to articulate or document this knowledge. The user firm may have purchased a unit of this equipment, and information required to solve a problem associated with this unit may be embodied in the unit. Thus the problem can be solved only if the supplier representative relocates to the site of the unit, or the unit including the information it contains is moved to the location of the supplier representative.

If it is costlier for the problem owner to move the person, then the equipment moves to the location of the supplier representative. However, if it is costlier to move the unit, then the supplier representative relocates to the user site. For example if air freighting a small defective component costs less than flying a knowledgeable person to the component, then the component will be shipped. In that case, the information that is embodied in the supplier representative is "stickier" than the information that is embodied in the component. However, if the problem unit is a three-ton ion implanter that has to undergo expensive installation procedures in order to function, then it is cheaper to send the supplier representative to site of the ion implanter. In that case, the information that is embodied in the ion implanter is "stickier." Thus if sticky information determines the locus of problem solving, the following hypothesis will be confirmed.

H3: *The locus of problem solving should occur at site that contains the stickiest item of information that is required to solve the problem.*

In an environment characterized by high potential loss rates, the speed at which required information can be generated, acquired and transferred is in general significantly more important than the cost of generating, acquiring and transferring information. For example, if a unit of equipment that normally processes one wafer per minute is idle, each wafer contains 200 microprocessors, microprocessors sell for $50 per unit, and the factory is operating under capacity constraint, then the chipmaker is losing $10 000 per minute in revenue because that equipment is not operating. Such loss rates dwarf all other considerations, including the process equipment's amortization rate, the salaries of the problem solvers, and the problem solvers' overhead costs. The loss of revenue due to delay becomes the dominant factor in calculating the true cost of information transfer.

The problem-solving process consists of six stages: problem detection; problem localization; problem identification; designing a fix; implementing the fix; and confirming the fix. Detection, localization, and identification are diagnostic steps, whereas designing and implementing a fix constitute repair activities. Confirming the fix represents an additional diagnostic step that is considered a necessary part of semiconductor manufacturing and process development. Chipmakers need to check whether the fix that they have designed and implemented actually works and does not create any additional unanticipated problems.

Problem localization is very important in semiconductor manufacturing and process development, because reducing the scope of a problem minimizes the potential damage that it can cause. For example, if the yield of wafers that emerge from a semiconductor manufacturing facility crashes from 90% to 10%, then the knowledge that the problem comes from metal coater #4 is very valuable. If coater #4 runs in parallel with other coaters, then the chipmaker can shut down coater #4 and repair it while the rest of the factory resumes production at high yield. The coater constrains the factory's capacity when it is down, but it no longer threatens the factory's total output.

III. Research Methods

The study consists of 69 cases of solved yield, process and equipment problems from all functional areas of integrated circuit fabrication, which have been provided by 37 industry experts in one-on-one interviews. The cases span the last quarter of the 20th century and cover semiconductor processes at all levels of maturity. The cases contain a sample of 398 non-trivial instances of user-supplier interaction (or noninteraction) involving 35 user firms and 23 supplier firms. The instances come from all stages of the problem-solving process. The problem owner, who is the user in 97.1% and the chipmaker in 98.6% of all instances, chooses the actor and the locus of problem-solving activity in each instance.

I have used very straightforward variables in this study. I have recorded whether the user, the supplier or a third party agent conducts problem-solving activity in a specific instance, and where the problem-solving activity has taken place. I have also estimated the maximum potential loss rate of the problem owner at each stage of the problem-solving process from information supplied by the respondents. I believe these estimates to be accurate to about $\pm 30\%$.

In spite of insistence by the respondents that the problems they recounted were "not unusual" in semiconductor manufacturing and process development, I cannot guarantee that the data in this study constitute a completely random sample. The method of interviewing the respondents may have exposed the sample of instances of problem-solving activity to expert bias, bias toward problem complexity and bias resulting from problem-solving path dependence. Expert bias could have resulted from the fact that all respondents possess college degrees or 10 years of experience in subject matter that is relevant to the problem under discussion. Respondents who did not were unable to recount the complete history of a problem from initial detection to resolution. Thus their recollections could not be included in the sample.

The high level of expertise of the respondents introduces bias toward high problem complexity into the sample. In general, problem solvers do not consider problems for which a straightforward trial-and-error path to the solution is readily apparent are matters that are worth discussing. A "true problem" tends involve a puzzle of some kind. A thin film deposition engineer explains.

> "Trying to optimize the thickness of silicon nitride (a deposited film) is not trivial, but it is not a real problem. If the film comes out too thick, then I can turn down the deposition time on the next cycle. (If it is too thin, one can do the opposite.) After about four or five batches (process cycles) the thickness should be near the center of the spec. A technician could probably do that without my help. …Something where I don't see the solution immediately (constitutes a real problem). If I have to spend some time trying to figure out what is going on, (then it may be a real problem)."

The path to the solution of a problem may also have an effect on decisions pertaining to the actor and the locus of problem solving, because upstream decisions may influence downstream decisions. For example, if the user of a technology calls a supplier specialist to identify the root cause of a problem, then he/she may be inclined to let that supplier specialist design a fix for the problem and implement the fix, instead of having the supplier diagnose the fix and the user implement the fix. The decision on whether to let the problem solver from the previous problem-solving stage continue with problem-solving activity or call in another agent may depend on economic factors such as labor cost, coordination costs, and the cost of transferring knowledge from person to person.

Expert bias, bias toward complex problems and problem-solving path dependence are inherent consequences of the interview process used in this study. This research paper can therefore not be viewed as an inquiry into generic problem-solving practices in semiconductor manufacturing and process development. It must instead be considered an analysis of practices that expert problem solvers in the semiconductor industry deploy when they try to solve the problems that are of great concern to them.

IV. Results and Observations

The respondents in this study report many occurrences of inter-organizational and intra-organizational conflicts, including some instances of what the respondents call "human drama." However, the recantations of the problems create the distinct impression that on average the problem-solvers in semiconductor manufacturing and process development are rational actors who are committed to solving problems as rapidly as possible, in order to avoid losses of revenue. In addition, problem-solving patterns throughout the semiconductor industry appear to be very similar; problem solving tends to follow the previously outlined six-stage process. Problem solvers attempt to localize a problem immediately after it is detected. Once the problem is localized, the problem solvers focus on finding the root cause of the problem. After identification of the root cause, they design a fix that they subsequently implement. Finally, the problem solvers check whether the problem has been fixed, and whether the fix has not caused any new problems.

The data in Table I, which consists of a sample of 57 cases for which potential maximum loss rates could be calculated, shows that the urgency of problem-solving activity varies greatly from problem to problem. The maximum potential loss rate of some problems exceeds $1.4 million per hour, whereas the loss rate of others is negligible. The loss rate also varies dramatically within each problem-solving stage and from problem-solving stage to problem-solving stage. A drop of a few hundred thousand dollars per hour across a problem solving stage is not unusual. The maximum potential loss rate can also climb when problem solvers increase their understanding of a problem and discover that the solution is more expensive or time consuming than had originally been anticipated. The data in Table I confirm that problem localization is the primary factor in reducing the maximum potential loss rate, once the problem has been detected. The mean maximum potential loss rate drops from $221 000 per hour after problem detection to $130 000 per hour after problem localization. No other problem solving stage induces such a large drop.

The data in Table II strongly reject hypothesis H1. Only in 11.1% of all cases do suppliers of technology conduct problem-solving activity at the supplier site. Therefore specialization cannot be the overriding concern of the problem owner when he/she chooses the actor and the locus of problem solving.

The data in Table II confirm hypothesis 2 at first glance. In 71.4% of all instances of problem-solving activity, a problem-solver from the user firm conducts problem-solving activity at the user site. One may therefore conclude that coordination costs are a significant factor in agency decisions. However, Table III shows that the choice of actor and the locus of problem solving are a function of problem-solving stage. In the detection, localization and confirmation stages, the user tends to engage in problem-solving activity at the user site to an overwhelming degree. However, the actor and the locus of problem solving vary greatly during problem identification, the design of the fix, and the implementation of the fix. Factors other than coordination costs must be at work during these problem-solving stages.

The data in this study strongly confirms hypothesis H3. I have observed 269 instances of user-supplier interaction in which one party possesses at least one item of sticky information that is required to solve a problem, and the other party lacks that item of information. In all 269 observed instances of sticky information, the losses in revenue due to delay in problem solving contributes more to the stickiness of information than the actual cost of transferring the information does. In 98.9% of these instances, the locus of problem solving coincides with the locus of the stickiest item of information that is required to conduct the required problem-solving activity. In the 1.1% of the 269 instances that involve sticky information a supplier or third party representative, who possesses nonsticky information that is required to solve the problem, just happened to be at the user site working on another problem. The supplier representative helped solve the problem at the user site even though he could have conducted the problem-solving activity remotely from the supplier site.

Problem solvers, who possess sticky information in the form of tacit knowledge, relocate to the site that contains an even stickier item of information in 12.3% of all instances of problem-solving activity. They do so even if this practice causes costly delays because information that is required to solve the problem cannot be transferred by any other means.

TABLE I
POTENTIAL MAXIMUM USER LOSS RATE AS A FUNCTION OF PROBLEM-SOLVING STAGE. SAMPLE SIZE = 57

	Potential Maximum Loss Rate ($/hour)			
Problem-Solving Stage	*Low*	*Mean*	*High*	*Std. Err.*
Detect	110	221000	1400000	43400
Localize	60	130000	1400000	34600
Identify	80	89000	700000	25200
Design Fix	70	47000	700000	15900
Implement	0	28000	500000	1400
Confirm	0	2000	60000	1100

TABLE II
DISTRIBUTION OF ACTORS AND LOCUS OF PROBLEM-SOLVING ACTIVITY IN PERCENT. SAMPLE SIZE EQUALS 398 INSTANCES OF PROBLEM-SOLVING ACTIVITY

Total (n=398)	*Actor* ------------------------------------>			
Locus	User	Supplier	Third Party	Sum
User	71.4%	7.3%	4.5%	83.2%
Supplier	0.8%	11.1%	0.3%	12.1%
Third Party	0.0%	0.0%	4.8%	4.8%
Sum	72.1%	18.3%	9.5%	100.0%

In all but one of the instances of problem-solving activity in which problem solvers change location to solve a problem, the problem solvers are representatives of supplier firms or third party firms that relocate to the user site. The user calls them into a user site to diagnose or fix a problem that the user cannot solve. These representatives may have seen how the same or a related problem was solved at the site of another, possibly competing chipmaker. The knowledge gained from these experiences may allow these representatives to solve the hiring user's problem by making associations that the local experts are unable to make. The hiring user, who has no knowledge of what other users do, has to rely on these external actors for help in solving a problem, in order to save precious time. A third party agent that was hired by a chipmaker to solve a lithography problem explains.

> "Once (the factorial design experiment showed that) photochemical "wetting" was the problem, I knew what to do. We had to replace the photochemical. …The local lithographers would have come to that conclusion, too, but I knew which photochemical to pick because I had seen similar wetting problems in other fabs. As a matter of fact, I worked on one (wetting problem) with another client. …The locals may have taken weeks to figure out which photochemical to use. They would have had to figure it out by trial and error, and there are dozens of photo chemicals that apply to this process. I know which one did not have the wetting problem, so I saved the locals a lot of time."

V. CONCLUSION

A. *Sticky Information and the Locus of Problem Solving*

Our study clearly shows that sticky information determines the locus of problem solving, which is predicted by [8]. If one party lacks an item of sticky information that is required to solve

TABLE III
DISTRIBUTION OF ACTORS AND LOCUS OF PROBLEM-SOLVING ACTIVITY AS A FUNCTION OF PROBLEM-SOLVING STAGE. "n" REPRESENTS THE SAMPLE SIZE

Detection (n=69)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	97.1%	0.0%	1.4%	98.6%
Supplier	0.0%	1.4%	0.0%	1.4%
Third Party	0.0%	0.0%	0.0%	0.0%
Sum	97.1%	1.4%	1.4%	100.0%
Localization (n=52)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	75.0%	0.0%	9.6%	84.6%
Supplier	0.0%	3.8%	0.0%	3.8%
Third Party	0.0%	0.0%	11.5%	11.5%
Sum	75.0%	3.8%	21.2%	100.0%
Identification (n=70)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	58.6%	11.4%	8.6%	78.6%
Supplier	1.4%	10.0%	0.0%	11.4%
Third Party	0.0%	0.0%	10.0%	10.0%
Sum	60.0%	21.4%	18.6%	100.0%
Designing Fix (n=70)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	50.0%	14.3%	5.7%	70.0%
Supplier	2.9%	25.7%	0.0%	28.6%
Third Party	0.0%	0.0%	1.4%	1.4%
Sum	52.9%	40.0%	7.1%	100.0%
Implementation (n=67)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	53.7%	16.4%	3.0%	73.1%
Supplier	0.0%	19.4%	1.5%	20.9%
Third Party	0.0%	0.0%	6.0%	6.0%
Sum	53.7%	35.8%	10.4%	100.0%
Confirmation (n=70)				
	Actor------>			
Locus	User	Supplier	Third Party	Sum
User	94.3%	0.0%	0.0%	94.3%
Supplier	0.0%	4.3%	0.0%	4.3%
Third Party	0.0%	0.0%	1.4%	1.4%
Sum	94.3%	4.3%	1.4%	100.0%

a problem, and the other party has access to that item of sticky information, then the locus of problem solving moves to the site with the sticky information. An employee of the site with the sticky information will be the problem solver unless he/she lacks an additional item of sticky information that is required to solve the problem.

Sticky information explains why the choice of actor and locus of problem solving depend on the stages of the problem-solving process. In the detection, localization and confirmation stages of the problem solving, sticky information that is required to solve a problem is located at the user site in the overwhelming majority of instances. The user of semiconductor process technology faces the challenge of combining these technologies into a full semiconductor process. Thus the user possesses knowledge regarding the interdependencies between individual process technologies that the suppliers of individual process technologies generally lack. For example, the chipmaker is much more likely to understand the physics of a semiconductor device that the chipmaker has designed. This puts the chipmaker in the ideal position to determine which process step or which piece of equipment is at fault, or to check whether a fix will cause any new, previously unforeseen problems in the semiconductor process. It would be difficult for a supplier of an ion implanter or a wafer stepper to make such attributions because these actors are not familiar with the chipmaker's process or procedures, and information regarding the process and procedures are notoriously difficult to document, encode, articulate and transfer.

In the stages of the problem-solving process that involve problem identification, the design of a fix and the implementation of the fix, sticky information that is required to solve a problem frequently resides at the supplier site or in the mind of the supplier representatives. For example, a user of a diagnostic tool would have trouble identifying and fixing a software bug in code that the supplier has written, because the subtleties of software are sometimes extremely difficult to document, articulate and transfer. Thus the supplier has to make many software edits in units that are in the field.

If two separate items of sticky information that are required to solve the problem are not co-located, then the less sticky item is brought to the site of the stickier item. In practice this means that a problem solver with tacit knowledge will move to the site hosting a problem that is embodied in the site. For example, if an idiosyncratic feature of the user environment mandates a software adjustment, then the supplier representative cannot make the upgrade from the supplier site. He/she must relocate to the user site to understand the problem completely before he/she tries to solve it. The third party agent from section IV faced an analogous situation. He/she had to explore the user environment to understand the root cause of the problem before prescribing a solution. He/she declares…

> "I could not have done this from (my home office), because I had to see what was going on in the fab to know that it (the problem) was wetting. I also had to understand what they were doing, in order to recommend the right photochemical."

B. A Shortage of Experts

It can be argued that sticky information constitutes a major source of coordination costs. The cost of moving an expert with tacit knowledge to the locus of problem solving, and more importantly the loss of revenue associated with travel time once a fault mechanism is active can be very high. This is especially true in the detection, localization and confirmation stages of the problem solving, in which site-specific knowledge is required to successfully engage in problem-solving activity. Finding an expert that understands both the specifics of a technology and the details of environment in which it operates generally takes

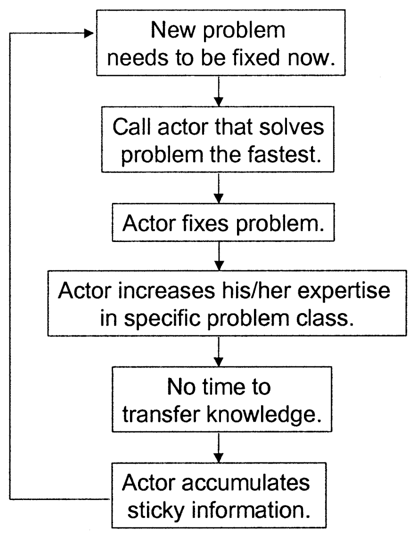

Fig. 1. The dynamics of expertise creation.

more time than a chipmaker with an active fault mechanism can afford to spend. Thus the chipmaker has an incentive to develop a problem-solving organization at the chipmaker's site [10]. The chipmaker hires problem solvers and lets them develop problem-solving expertise by solving actual problems; only under exceptional circumstances will the chipmaker hire an outsider to engage in problem-solving activity. Over time the local problem solvers accumulate tacit knowledge in most problem classes that pertain to the chipmaker's problem-solving needs, which allows them to respond to a problem without significant travel time or extensive learning periods.

Unfortunately, acquiring knowledge related to maintenance, individual process technologies and the integration of process technologies involves prolonged periods of trial and error, and transferring knowledge to others requires extensive training programs and socialization activities between employees that possess complementary knowledge [11]. Few chipmakers can thus afford to invest in the developing experts in all problem classes. Instead, most chipmakers are forced to contract out problem-solving tasks to suppliers of technology and third party agents in areas where they themselves lack sticky information that is required to solve a particular problem.

Fig. 1 shows how contracting out problem-solving activity under time pressure is creating a shortage of problem solvers in semiconductor manufacturing and process development. A chipmaker detects a problem that needs to be solved urgently because it is inducing a high loss rate. The chipmaker calls the actor who he/she believes will solve the problem the fastest. The actor fixes the problem and accumulates expertise while solving the problem. Unfortunately, there is no time to transfer the knowledge that has been gained. The problem solver carries the knowledge inside him/her and applies it to related problems. His/her reputation for solving problems of a certain type increases with every iteration of the cycle in Fig. 1. Users begin to prefer this actor to any other, and they cease to develop expertise of their own. Expertise concentrates in the minds of a few people, who have increasingly less time to transfer information. A third party agent recalls an instructive case.

> "(A semiconductor manufacturing firm) had a recurring problem that came back once again. …This time, the vice president (of the semiconductor manufacturing firm) asked for me by name. He knew I could solve the problem, because I had solved this problem and similar problems at their site before. …I guess you get a bit better at something every time you do it, and I guess I had gotten good at (solving this problem type). …Sure, ultimately they (the user's problem solvers) would have solved the problem without me, but it would have taken them a long time, and they would have lost a lot of money. It was more cost effective for them to call me. …The last time I was out there, I could have trained some of their local experts to solve the problem, if it would come back. Unfortunately there was no time. They were busy solving other problems."

Many suppliers of semiconductor process and analysis technology have taken the initiative in reducing the cost of problem solving. They have cut the coordination costs of leading semiconductor manufacturers by moving field service teams into the vicinity of major semiconductor manufacturing facilities. This practice enables specialists to engage in problem-solving activity, which increases problem-solving productivity and decreases the cost of information transfer. Should the solution of a problem require the tacit knowledge that is embodied in the mind of a supplier expert, said supplier expert will no longer have to fly for many hours to get to the locus of problem solving. He/she will essentially be at the user site, accumulating user-specific and site-specific tacit knowledge that will make him/her a site expert. However, developing a site expert takes time, because the supplier representative has to learn about the idiosyncrasies of the new site. The technology integration manager from Section II comments on this situation.

> "The supplier reps may know a lot about their technologies, but that does not mean they can just come in and solve our problem. By the time we explain to them what we are doing here, we can fix the problem ourselves."

Unfortunately, user-specific expertise and site-specific expertise come at a high price. If the supplier representative is transferred to another user site or even another site of the same user, much of the supplier representative's accumulated expertise will be lost to the original user. In addition, much of the site-specific tacit knowledge that the supplier representative has accumulated will be of little value at the new site. If the supplier representative does not transfer, then he/she is unable to acquire tacit knowledge about the performance of the supplier technology in other user environments. The supplier representative will be less valuable to a user because he/she may lack insight that could accelerate problem solving. In all cases, sticky information limits the problem-solving capabilities of all concerned parties.

VI. The Remedy: Process Toolkits

In order for the efficiency of problem solving to increase, the supplier and the user need to find ways to "unstick" information [8]—he/she needs to invest in technology that decreases the total cost of information transfer. The supplier can unstick information by providing a toolkit that enables the user to engage in problem-solving activities without having any understanding of what the supplier does [12]. ASIC design works on this principle [13]. The semiconductor manufacturer provides the circuit designer with a toolkit that allows the designer to achieve his/her goals without a deeper understanding of the semiconductor process that will fabricate the designs. Similarly, suppliers of diagnostic tools and services are currently creating toolkits that combine defect detection, defect analysis and defect sourcing into one operation that can be conducted in real time. The user can identify the source of a defect without knowing much about the system that provided the diagnosis.

A toolkit generally includes a set of design rules, which a user must follow in order to be guaranteed a working design. Toolkits tend to create agency effects [13], which are defined as misalignments of interests between users and suppliers [14]. Users want to push the envelope of performance, whereas suppliers want to come up with one adequate solution that fits all users. Agency effects exist in the semiconductor industry, when leading semiconductor manufacturers want to acquire or develop leading edge process technology to differentiate themselves from their rivals, while suppliers of process technology want to develop one solution that fits all their customers.

In order to minimize the cost of information transfer, the process technology suppliers will have to have their way. They will provide a toolkit of standard process recipes that chipmakers will use as building blocks for full semiconductor processes. (This toolkit will most likely be developed in partnership with leading-edge chipmakers.) Chipmakers differentiate themselves by combining process technologies in unique ways and by adding proprietary process technologies, which they will have to sustain on their own. Leading edge chipmakers also gain competitive advantage by an accelerated learning curve.

The reduction in complexity that results from less variation in process technology allows suppliers to take advantage of the economics of specialization. No sticky information exists in the user environment once one process recipe is essentially common to all users. Supplier specialists are then able to remotely monitor the status of hundreds of pieces of equipment at multiple user sites. Information is gathered via *in situ* sensors and transferred to a centralized monitoring agency via the Internet. Remote fixes from that agency via telepresence or virtual reality links may also be possible.

Chipmakers still have to solve problems that involve interdependencies between process technologies, which suppliers of constituent technologies are not able to diagnose. However, the number of experts required solve problems in processes that are assembled from standardized building blocks drops dramatically when the nature of the building blocks is understood. Similarly, a small number of supplier specialists can monitor the performance of a large number of essentially identical building blocks. It therefore appears as if process toolkits reduce the cost of information transfer, which will increase profitability in the semiconductor industry by unleashing the power of specialization.

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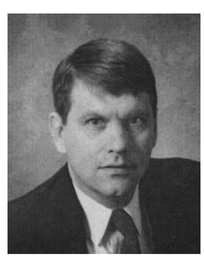

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