THE USE OF GRAPHIC REPRESENTATIONS IN SEMICONDUCTOR ENGINEERING TEAM PROBLEM SOLVING

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Starting with the assumption that graphic representations contribute to design problem solving, this paper reports an experiment in which the performance of multidisciplinary engineering problem solving teams in the semiconductors industry was compared under four different conditions pertaining to the graphic data they received. These conditions ranged from no graphic data to all available graphic data, with two intermediate conditions, in which either generic graphic representations alone were provided, or only domain-specific representations were supplied. It was found that graphic representations enhance the construction of shared team mental models of the problem and its envisioned solution, and the teams that received a lot of graphic data scored highest for their solutions. However, participants reported problems understanding domain specific representations. Conclusions pertain to the structure and norms of the industry and the state of the art of engineering education.

Keywords: Mental models, Problem solving, Graphic representation, Semiconductors.

1. INTRODUCTION: THE PROBLEM

Many large engineering endeavors are dispersed nowadays over several sites, each with a different specialization. This is the case of the semiconductors industry, where design and production are often carried out in separate plants, as manufacturing is outsourced to an independent silicon fabrication site which may be thousands of miles away [1]. Fear of industrial espionage is responsible for the fact that only minimal information is transferred from the design team to the fabrication plant. When fabrication goes well, this is enough. However, fabrication problems are not infrequent, resulting in malfunctioning electronic devices that do not perform as expected, in which case the cause of the problem must be detected and a solution must be devised. Interdisciplinary task teams are appointed to solve such problems; they use the information available which is often insufficient, requiring an expensive, time consuming process of reverse engineering.

This raises a number of interesting questions pertaining to issues at the macro and micro level, such as the structure of the industry and the relationship between design and fabrication which is both collaborative and adversarial; the effectiveness of problem solving within an interdisciplinary team, primarily as regards the mental model they are or are not able to share of problems, probable solutions

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and problem solving processes and methods; and information representation types and their efficacy in the problem solving process.

Typically, semiconductors fabrication plants employ professionals from various disciplines, such as mechanical, materials and electrical engineering, as well as physicists and chemists. Interdisciplinary problem solving teams are therefore composed of members from these fields. Our observations indicate that teams have difficulties sharing clear mental models of solutions and problem solving processes. Standard problem-solving methods are used, primarily the so-called six-step methodology [1], but this does not appear to be very effective as solving problems actually takes weeks, months, even over a year. In this paper we present empirical research focused on the type of visual information used by problem solving teams and its effect on team processes and solution quality. We start with a brief overview of mental models at the team level, and proceed to classify graphic representations, or visualizations, used in design and problem solving. We then present our empirical study and discuss its results, terminating with some broad conclusions at the macro and micro level.

2. SHARED MENTAL MODELS IN TEAMS

The term 'mental model' refers to the way people think and reason about the world: the mind creates reduced and simplified models of reality which serve us in understanding how things work in the world, including human behavior. The idea goes back to Greek philosophy, and was introduced to the study of human behavior and cognition by Craik [2], and more recently by Johnson Laird [3] and Gentner & Stevens [4], among others. A mental model is an inner representation that allows us to describe objects, people, situations, systems (goals, forms, functions) and concepts, and predict their future development or behavior relative to a given state. In problem solving in particular, we develop separate models for the task goals, the process, the expected outcome, team performance (if applicable), and more [5–7]. Individuals construct mental models based on their knowledge and past experience. In a team, each member has his or her own mental models, but to be effective the team must share metal models and in order to do so those models must be at least partially externalized, so members can discuss and negotiate their viewpoints and hopefully arrive at sufficiently shared models to allow a coordinated effort, building on the different(agreed upon) strengths within the team.

Since mental models are based first and foremost on knowledge and experience, interdisciplinary teams bring to the discussion table different disciplinary contents and conventions, but also different standard representations, both in terms of terminology and conventions of graphic representations. Many of these are specialized and require initialization into the discipline in order to be understood. For example, electric circuit layouts are not necessarily well understood by physicists and sections through complex machine parts may not mean much to chemical engineers. In the design of tangible objects and in problem solving efforts due to device malfunctioning, graphic representations may be necessary for the creation of a shared mental model in a team which is jointly engaged in design/problem solving [8]. Let us therefore devote a brief section to the kinds of graphic representations used in many engineering domains, and in particular in the semiconductors industry.

3. GRAPHIC REPRESENTATIONS–GENERIC AND DOMAIN SPECIFIC

Visual information processing is indispensible in many reasoning, imagining and problem-solving tasks, as some information is easier to express and comprehend when represented visually than by language [9, 10]. The kind of representation, or display, used in problem solving affects the decisions made by the problem-solver(s) [11]. Graphic and other visual representations have served humans to communicate ideas and solve problems from the dawn of history; we need only think of prehistoric cave drawings and various faith-related symbolic objects to confirm this assertion. By graphic we mean two-dimensional representations such as drawings of one sort or another, pictures, diagrams, maps, icons and more [12]; other representations may be three-dimensional, such as scale models. Specific graphic representational systems were invented in the course of history for various purposes (we do not include here alphabets or numerals), for example for the notation of music and later dance, for cartography and nautical cartography, for standard signage such as road or safety signage, and so on. In the realm of design the orthogonal projections system of specifying any object or space has been, since the Renaissance, the standard and universal representational system, used by architects, engineers and designers, as well as by construction and manufacturing personnel. Some of these representations, such as simple floor plans, are in common use wherever people require information to help them understand spaces and navigate through them [13]. In the sciences generic graphic representations across domains include, first and foremost, graphs. A number of standard graph representations are so ubiquitous in the description of quantitative relationships and dependencies that every modern word processing system, such as the one with which this text is written, includes them as a matter of course.

Almost all of the examples above are of generic graphic representational systems, understood by the populace of practically all but the entire world. An exception might be some of the varieties of orthogonal projections, such as sections, which require more mental imagery and abstraction abilities and some experience in using them. We may therefore classify sections in our next category of graphic representations–domain specific ones. What are domain-specific graphic representations, and in particular, what are they in the field of microelectronics, and specifically semiconductors?

Certain domains have, over time, developed specific graphic representational conventions to suit their needs. The degree to which such domain-specific visuals may be understood by 'outsiders' to the domain may vary, as we have seen with the example of sections or comparable drawings. The various technical domains of engineering and related fields use a variety of diagrams and other dedicated graphics to denote states and processes in each field. Consider for example chemical diagrams or electrical diagrams, which are not necessarily readily accessible to laypeople.

In the semiconductor industry, each process stage has its own unique visual representation, universal or domain specific, as seen in Figure 1. At the system level the functionality of the overall system is represented by diagrammatic building blocks of each function. The logic level is represented by the Boolean value of each building block, later on translated into a transistor representation at the circuit level. At the next process stage, the layout level, the transistor representation is transformed into physical layout diagrams, consequently used for the fabrication stages of the electrical device (all of these representations are employed during the R&D process stage). The fabrication, or technology stage, represents the device using pictures and schemes of the physical layout, but also all previous representations, to achieve a better understanding of the device's design. The main standard design representation format is the Graphic Data System (GDS) layout, which is used to outline the specific areas that are to be processed during the manufacturing steps (Figure 2a). Its main users are the device designers but this digital file may also be used for the manufacturing of the photolithography masks in the actual fabrication process.

A high resolution microscope picture is another common visual representation used in the industry. In addition to the standard Optical Microscope, the Scanning Electron Microscope (SEM) provides

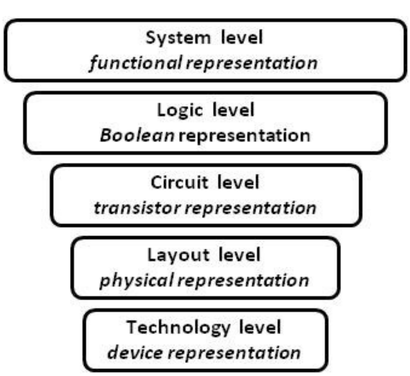

Figure 1. Representational norms in the semiconductors industry, at different levels.

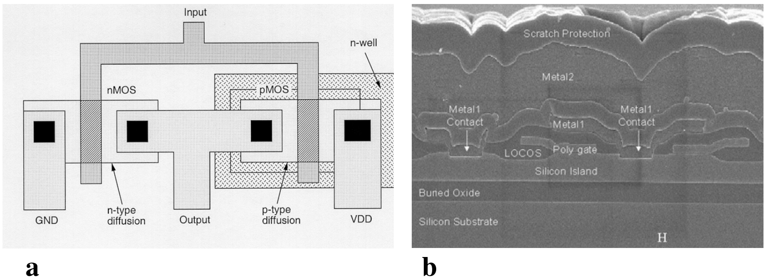

Figure 2. Domain-specific representations in the semiconductors industry (a) GDS layout [2]. (b) SEM picture [3].

sub-micron pictures of the silicon device. This imaging method allows us to view this small-scale structure from within by performing a cross section sample. The technique provides a gray-scale 2D picture (Figure 2b). Different substrates/materials appear in different shades of gray along with recognizable texture differentiation. In post-manufacturing problem-solving the relevant graphic representations are the GDS and SEM, in addition to generic representations such as graphs.

We are now ready to look at problem-solving teams' usage of each of these representations.

4. EMPIRICAL STUDY

The purpose of the empirical study was to find out how the use of different visual information packages contributes to the construction of a team's shared mental model of the problem and a vision of its solution, and how it affects problem-solving outcomes. Based on the literature, our assumption was that visual material positively contributes to the construction of shared mental models and therefore to the problem-solving process.

4.1. Experimental setup

The empirical study was carried out in the normal work-context of a semiconductors fabrication plant. 16 teams of two members each were asked to solve two typical manufacturing problems, similar to the ones they encounter in their routine work in the foundry. All team members were process engineers from different disciplines. Team members were assigned from various fields. Each team was asked to conduct a problem solving session limited to one hour (but they were allowed to run overtime). The data the teams received differed in terms of the visual material provided; there were four different data package categories, namely: (a) no visual data; (b) pictures (SEM) only; (c) graphs only; and (d) all available data (including a GDS diagram). Four teams were assigned to each data category. All sessions were video-taped and when they ended participants answered debriefing questions.

The solutions the teams reached were assessed by three naïve judges who are experienced senior engineers in the foundry. We examined not only the precision and quality of the solutions the teams arrived at and the time it took to do so, but also the contribution of each visual representation type to the formation of the shared team mental model (and thereby to the overall performance of the team).

4.2. Results

Based on self-reports by team-members, the contribution of visual information to the solutions of the engineering problems presented to them was analyzed relative to the data package provided and to problem solving stages (Figure 3). Results show that there is a strong correlation between the visual information provided to the team and its contribution to the team's shared mental model in the early stages (problem definition) of problem solving.

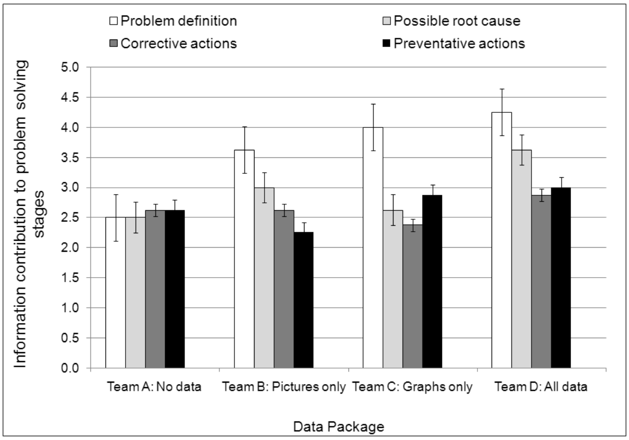

Figure 3. Visual data contribution to solution stage (mean±SD).

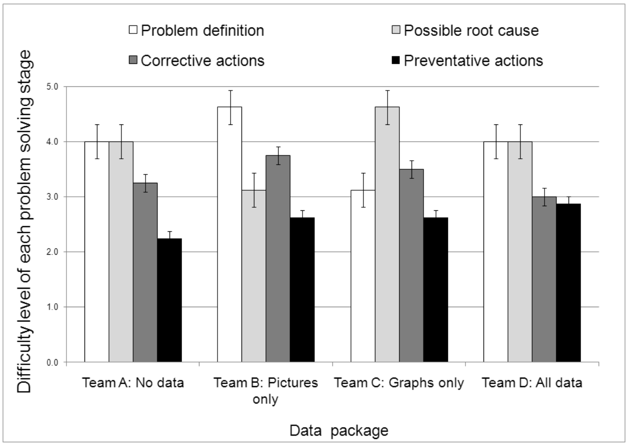

Figure 4. The most difficult stage (mean±SD).

When asked about the hardest and longest problem solving stages, the teams that were given the ‘pictures only’ package reported that the early stages of problem solving, i.e. problem definition, was significantly harder and longer compared to the reports by the ‘graphs only’ teams (Figures 4 and 5).

Each team member was asked to report the effectiveness of the visual information provided (Figure 6). Results show that the effectiveness of GDS representations was significantly lower than other generic and domain-specific representations.

The final grades given to the teams’ solutions by three naïve judges (blind to the study’s objectives) were reviewed relative to the visual information data package categories. Results (Table 3.1.) show that the highest grade was won by the all-data group. Second was the group that used no visual data, followed closely by the group using graphs only. The picture group received a significantly lower grade than all other groups.

A look at the time to solution shows that the team with the highest grade (all data) worked slightly longer than the groups that worked with graphs or with no visual representations at all, but the pictures group worked even longer, although the extra time spent had no beneficial effect on the quality of the ensuing solution.

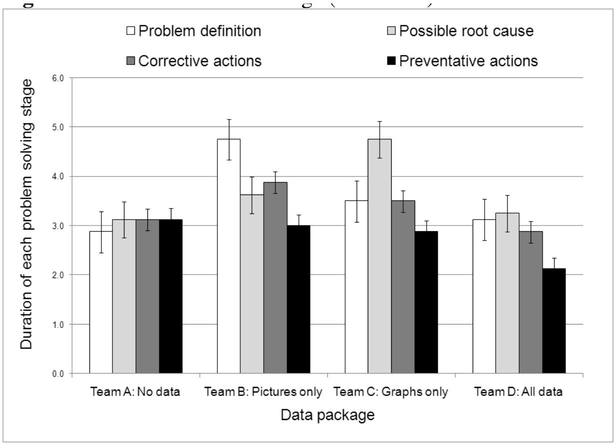

Figure 5. The longest stage (mean±SD).

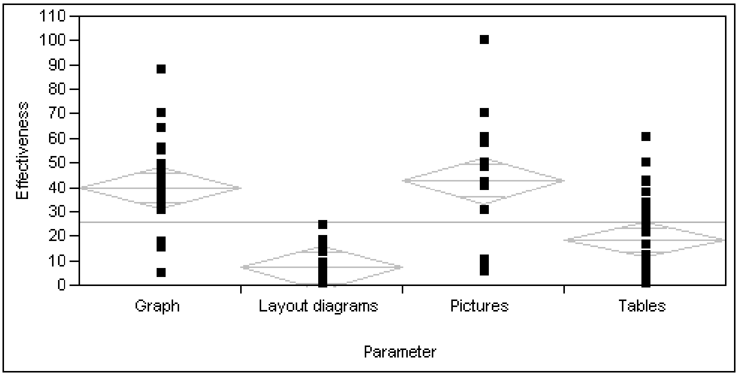

Figure 6. Effectiveness of visual representations in problem solving.

Table 1. Judges' grades and time to solution.

Visual Data Package Category	Mean grade by 3 judges (S.D.)	Time to solution (minutes)
All data	82.7 (6.4)	70
No visual data	70.7 (4.0)	65
Graphs only	68.3 (5.5)	68
Pictures only	54.0 (3.6)	72
Mean	68.9	68.75

We proceeded to interview another group of 30 process engineers from the same foundry regarding their experience with GDS layouts. Here too, we found that even experienced engineers reported difficulties using these diagrams. We checked their responses against academic background and discovered that there was very little difference among mechanical engineers, chemists, materials engineers and others who participate in integrated problem solving teams. Gender and amount of experience were also not correlated with the ability to understand and use GDS layouts.

5. DISCUSSION AND CONCLUSIONS

The results of the experiment showed that whereas the visual data had a demonstrated impact on teams' performance and helped create shared mental models of the problems, different types of diagrammatic representation varied in their contribution to the process of problem solving (in addition to the quantitative results, we rely on participants' self-reports during debriefing and on video recordings of the sessions). Surprisingly, GDS diagrams contributed next to nothing and many participants reported that they were not able to understand or use them. Some of the participants had never used these diagrams before and others, although familiar with the format, still found that deciphering them was too time and energy consuming. SEM pictures, which should have been understood by the participants as they are frequently used in problem solving, also posed great difficulties, possibly because most participants are not trained in technical drafting and sections in particular are hard for them to interpret. The teams using graphs only reached average results: both their grades and the time it took them to reach solutions were practically identical to the averages of these two parameters across conditions.

This seems to suggest that the use of universal representations, which are well understood (as reported by the participants), makes life simple; users reach satisfactory results but these representations do not promote more inquiry and outstanding performance. The use of representations that are not well understood is costly in terms of time needed to try to interpret them, not necessarily leading to satisfactory results. Not surprisingly, no visual data at all shortens the process since there is no need to try to decipher representations. In this case the nature of the problems made it possible to reach satisfactory solutions at the absence of any visual representations. It is noteworthy that the teams that received all visual data, although they needed a little more time to inspect and interpret the data, outperformed the other teams despite the fact that some of the visual formats were difficult for them (GDS layouts and SEM pictures). This appears to suggest that the opportunity to use a wealth of visual representations is the best choice in problem solving, even if some of the representations are somewhat obscure to at least some team members. The extra time dedicated to the examination of the available representations seems to have been well spent as it had a positive impact on the teams' collaborative behavior.

In interpreting these findings it was concluded that the industry is not well coordinated internally and externally, with substantial financial consequences due to problem solving difficulties. Internally, because the industry is divided into separate design plants and manufacturing plants, with a conceptual and practical gap between the two. Conceptual, because the standard use of GDS layouts in design and the reading of SEM pictures have not filtered down to manufacturing sites. Practical, because due to fear of industrial espionage design units do not share sufficient product specifications with troubleshooting manufacturing teams, which obliges the latter to engage in difficult and time consuming reverse engineering processes.

External coordination has to do with engineering and science education. Whereas manufacturing plants typically employ electric, mechanical and materials engineers as well as chemists and physicists who work in interdisciplinary teams, most educational programs in these disciplines do not teach domain specific representation conventions. Foundries have overlooked this knowledge gap and failed to offer their own in-house professional training that would allow team members from all disciplines to share a variety of representations so as to be able to readily form critically necessary shared mental models of problems and candidate solutions. Improved 3D applications for graphic data and SEM Cross Section displays may reduce the understanding gap and improve the problem solving cycle time.

At a meta-level, we may ask questions about design and the scope of responsibility it carries with it. For the benefit of all concerned, the semiconductors industry should re-think its current structure and business models, wherein design is disconnected from manufacturing. Shared representational norms and conventions would contribute to cost effectiveness and sustainability.

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NOTES

1 In the experiment reported in this paper the methodology was collapsed into four steps, as follows: Problem definition; Possible root cause; Corrective actions and Preventive actions.
2 Source: http://lsiwww.epfl.ch/LSI2001/teaching/webcourse/ch02/Figure-2.10.gif.
3 Source: http://www.nxp.com/news/backgrounders/bg9809.