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Study of Interdisciplinary Visual Communication in Nanoscience and Nanotechnology*

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This study uses an experimental approach to explore the relationship between individuals' disciplinary backgrounds in engineering and how they draw objects that are common to different disciplines within nanoscience and nanotechnology. We recruited graduate students (n = 16) from three engineering disciplines at the University of Washington. We report responses to a design task where subjects were asked to draw diagrammatic representations that captured their interpretation of disciplinary prompts from three areas of engineering—Biological Engineering, Chemical Engineering, and Electrical Engineering. Findings highlight two important elements of modern academic scholarship and teaching in engineering: (i) baseline visual communication competency appears to be higher than anticipated; (ii) interdisciplinary boundary-crossing appears to be on the rise, because while there are disciplinary biases it appears that there are much fewer than expected. We discuss implications of these findings for teaching in areas such as nanoscience and nanotechnology and suggest future avenues that might elaborate on related questions pertaining to disciplinary boundary-crossing, nanotechnology and visual design.

Keywords: nanotechnology education; science and engineering visuals; visual communication; interdisciplinary education; boundary-crossing, multidisciplinary education; graduate science education

1. Introduction

In this study, we sought to understand whether disciplinary backgrounds affect the visual communication practices of graduate students engaged in nanoscience and nanotechnology research. Our interest is in understanding barriers to successful collaboration in this important interdisciplinary area. Nanoscience and nanotechnology is a field broadly defined as the fabrication, manipulation, and characterization of materials that have at least one dimension at the nanometer scale. Many science and engineering disciplines have "converged" at this length scale with common goals and interests. Unlike other interdisciplinary fields (e.g. biochemistry, neuroscience, computational biology, etc.), formed by the merged interests of two or perhaps three traditional disciplines, the contributors research in nanoscience and nanotechnology tend to be more diverse, yet interconnected—a single experimental study often requires expertise from multiple science and engineering disciplines including chemistry, physics, biology, materials science, electrical engineering, chemical engineering, mechanical engineering, biomedical engineering, and other departments [1].

An example of a nanoscience research area is the use of DNA as a structural nanoscale building material to make sheets, tubes or little machines [2]. Designing the DNA sequences to fold in a prescribed fashion draws on expertise from biology, biochemistry (DNA synthesis and hybridization kinetics), and computer science (computing a viable folding structure). Papers resulting from research like this are published in nano-related journals, which are potentially read by audiences spanning multiple disciplinary arenas. The attention garnered by the promise of innovation in nanoscale research is resulting in publication rates growing faster than other broad categories of science research [3]. Faster publication rates also contribute to boundary-crossing and multidisciplinarity. Today, researchers create figures (graphs or schematics) for journal articles that convey complex

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arrays of data in colorful displays. Visuals occupy a significant fraction of the real estate of journal articles [4]. The journals that publish nanoscale research (e.g., *Nano Letters, Small, ACS Nano*) capitalize on the visual impact of these figures as well. *Nano Letters* introduced a visual table of contents—a graphical abstract for every article—from its first issue. In a field with multiple disciplines, quality visual communication with the capacity to transcend disciplinary boundaries becomes invaluable [5, 6].

Scientists and engineers rely on diagrams, figures, and graphs to assimilate information, perceive trends, and conceptualize spatial relationships that relate their message to peers and colleagues across disciplines [7, 8]. Photo-and micrographs capture transient phenomena via imaging instrumentation, data plots map arrays of numbers into perceivable structures, and schematic diagrams enable the spatial perception and manipulation of objects [9]. Engineers use abstracted visual representations when problem-solving. Disciplinary norms and practices accumulate so that representations become familiar and codified over time, e.g., biology [10], chemistry [11], and physics [12]. Having thus evolved within field boundaries, drawing conventions may become abstract, specialized, or diverse as the field matures [5]. Individuals who (either deliberately or haphazardly) build expertise in a field often learn to interpret and advance subtle visualization variations in what is referred to as "learning the visual language" [8]. For instance, practiced experts in highly specialized fields [e.g., 13–15] develop skills to assimilate details in complex visuals that communicate large patterns and complex trends. Similarly, abstract mathematical diagrams can facilitate complex thinking, but require interpretive skills developed only through extensive exposure [16]. Effective interpretation of diagrams may also involve a degree of cultural competence developed through exposure to the field—knowledge of the unspoken rules for presentation that are learned, but not taught [17]. This cultural competence may also involve a deep understanding that comes not just from learning concepts, but from experiencing how data is gathered and experiments are conducted in the field and in the laboratory. Lacking this deep knowledge, scientists may make errors in interpreting visual representations from other disciplines despite being very familiar with the display conventions [18].

In a multidisciplinary field that is trying to become interdisciplinary, many potential avenues exist for increasing cross-disciplinary understanding and collaboration. Determining how to provide students with educational experiences that encourage them to adopt related disciplines' perspectives, language, and knowledge structures is a major theme in nanotechnology curriculum development [19–22]. Many researchers and teachers recognize that in order to sustain the rapid growth of this field, new students need to be trained in multidisciplinary environments where strong visual communication may be key to building curriculum that integrates expertise across disciplines [19, 20, 23]. A consequence of the multidisciplinary environment in nanoscience and nanotechnology is that visual communication of the same object may not always occur in the same fashion. For example, the same component may be used for different purposes in different experiments and as such may be represented differently (Fig. 1).

Visual communication in nanoscience and nanotechnology, its benefits and its challenges to the education of undergraduate and graduate students has already been extensively explored with models and simulations [27, 28]. Here, we focus our study on a different subject: the visual communication of research findings between researchers in nanoscience and nanotechnology. At the focus of our research questions are differences in representation. Since disciplinary traditions may place emphasis on different roles for a particular material, we were interested in learning if disciplinary biases would prevail. Would visual representations differ when researchers from different backgrounds approach the same experimental purpose? In an experimental setting, we posed a cross-boundary graphical problem to scientists and engineers who came from different disciplinary backgrounds in order to investigate how their visual representations vary, and to gather insights into the choices they made when creating visual representations of recent research findings in nanoscience and nanotechnology.

2. Methodology

We recruited graduate students who self-identified as nanoscience and nanotechnology researchers and

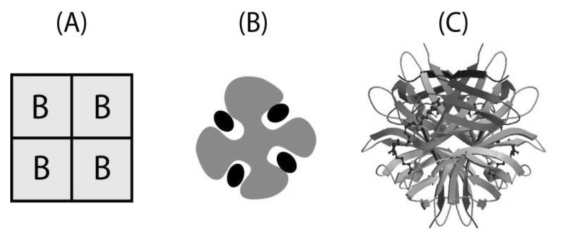

Fig. 1. Different representations of the protein streptavidin bound to four biotin molecules. (A) Schematic diagram of biotin, represented by the letter "B" and streptavidin, shown as boxes; (B) black ovals as the biotin molecules within a blob of streptavidin; (C) calculated protein crystal structure of streptavidin and biotin molecules. Adapted from [24–26].

tasked them with drawing representations of nanoscience and nanotechnology experiments (extracted from current literature). We obtained permission from the University of Washington Internal Review Board (IRB) to conduct research using human subjects. Students were videotaped as they drew while thinking aloud. When they completed this task, each student was interviewed for further insight into their thinking.

2.1 Participants

Subjects consisted of sixteen graduated students from the University of Washington who were enrolled in science or engineering degree programs spanning three disciplines: chemistry (n = 6), electrical engineering (n = 6) and bioengineering (n = 4). Demographic data about each participant was captured via questionnaires. This data included: previously earned degrees; self-reported competency in basic science subjects; specific training in nanoscience and nanotechnology and information about their experience with graphic design.

2.2 Prompts

We used four written prompts. The first prompt served as practice and instructed participants to draw an aspect of their own research. This prompt was intended to familiarize participants with the think-aloud and drawing processes and no data from this prompt is included in our analysis. The other three prompts were summaries of previously published nanoscience and nanotechnology publications [29–32]. The full text and citation for each prompt is in Appendix A. These prompts were chosen to highlight a combination of themes, methods, and materials often used in nanoscience and nanotechnology. For instance, the chemistry prompt examined the effects of surface modification of quantum dots, which are very small (< 10 nm), light-emitting semiconductor crystalline particles; the electrical engineering prompt described the structure of a transistor in a 1 nm diameter nanotube made of carbon; and the bioengineering prompt described three methods for constructing and optimizing a device that would sense the presence of a specific biological molecule. For each prompt, participants were supplied with a small, portable whiteboard (~14" × 24"), four colors of dry-erase markers (black, red, blue, green), and an eraser. All participants signed a consent sheet in compliance with IRB approval from the University of Washington.

2.3 Procedure

Participants were presented with the first prompt, whiteboard, and markers. They were instructed to begin by reading the prompt aloud, and then to continue verbalizing their thought process (think-aloud) as they drew. One researcher remained in the room, but sat in a way to discourage interaction with the participant [33]. If the participant went for 10 seconds or so without verbalizing, the researcher reminded him/her to be mindful of the think-aloud. Upon completion of each drawing, the participant was provided with a clean whiteboard and a new prompt. The prompts were given in the same order for all participants: (A) their own research, (B) chemistry, (C) electrical engineering, (D) bioengineering.

When all the drawings were complete, each participant was interviewed—asked to describe what they were thinking as they completed each drawing. The following is an example of engaging the candidate about their drawing:

> [Pointing to the finished drawing] "Please walk me through what you have drawn here."

The following is a sample disciplinary—boundary-crossing—question:

> [Subject's disciplinary expertise is the same as the prompt] "Suppose you were a chemist [different discipline] would you have drawn the same?"

2.4 Coding

Participant drawings were analyzed under the categories of accuracy and appearance. We devised a rubric that defined, within reason, objective measures that were used to judge each drawing. Drawing accuracy was straightforward, because experts could easily determine if a drawing represented the prompt with reasonable faithfulness. From that, an accuracy component was given a rating with a score as follows: not shown (0), shown vaguely or inaccurately (1), or shown with correct detail (2). An appearance rubric, because of the inevitable subjectivity connected with this space, proved a little more difficult to construe. The wisdom of discipline-specific scientists and design exerts was solicited in order to manifest an acceptable appearance rubric that we could live with. After discussion, team members were able to agree on components that were visually represented and portrayed with some rigor the intent of the prompt.

A percent (~80%) of the data was scored blind by three members of the research team. Cronbach's alpha [34] was used to establish inter-rater reliability (> 86% agreement). Disagreements were resolved through discussion before proceeding with coding the remaining data. Coded data was analyzed using SPSS.

PROMPT B (Chemistry)	The ligand representation is				Ligand exchange is		
	not shown	object other than a line	line only	line with functional group	not shown	trivially shown	shown with detail
Bioengineering	0	0	1	3	0	2	2
Chemistry	0	0	1	5	0	0	6
Electrical Eng.	4	1	0	1	3	2	1

Fig. 2. Types of representations of ligands and ligand exchange versus disciplinary background.

3. Findings

In this section we present findings that emerged from our investigation; findings are described from quantitative and qualitative data. We begin with the drawings themselves and how the students dealt with them. Next we give results of the "think-aloud" reporting and erasures. Finally, we focus on the student interviews and the perspectives we gleaned from them.

3.1 Drawings

This study emphasizes that there are no strong correlations between disciplinary training and graphical representations as observed either by *accuracy* of graphical representation or *appearance*. There were however, nuances in the findings that seemed to confirm the existence of pockets of scientific knowledge that tends to stay within discipline. We highlight quantitative data that suggests a disciplinary bias in scientific fields, which might be sufficiently difficult or isolated that they fail to cross-disciplinary boundaries. It could also suggest that these elements consist of higher-level concepts that remain independent of disciplinary training. In Fig. 2, for instance, we show the results of tabulating the coded representations of Ligands by Participant Discipline. The shaded boxes highlight the majority response of students within each disciplinary group. A chi-square test of independence between participant discipline and ligand depiction found that there was a significant difference in how students from the different disciplines chose to draw a ligand [χ^2 (6, N = 16) = 12.37, p = 0.05].

In the accuracy coding, the drawings by the chemistry students were sufficiently detailed, while the bioengineering students were split: some drew a detailed representation and others made only vague, visual "translations" of the text: (e.g., an arrow with the words "ligand exchange" next to it). Again, in a chi-square test of independence between participant discipline and ligand depiction for accuracy, we find discipline-dependent results for drawn representations of ligand exchange as we do for the ligands themselves [χ^2 (4, N = 16) = 11.41, p = 0.02].

This analysis was repeated for each of 46 different components from the three prompts. The components that showed statistically significant ($p < 0.05$) disciplinary differences are highlighted in Fig. 3. These components predominantly show the same knowledge pattern as the ligand example. In other words, only a handful of components result in a statistically significant discipline-driven difference between participants.

3.2 Think-aloud

We were also surprised by how little information we were able to glean from the student think-aloud effort. We had anticipated that their thought processes would give insight into representational choices made as they worked through their drawings, but most utterances dealt with figuring out the content embedded in the prompts. Only a few comments suggested representational choices. We give a few examples here to show the impact of their thinking on their drawings.

> No. 1 (Chemist): Um, so . . . I think the way I've often seen this is there's like, a little triangle. So this is . . . would be like, biotin . . . er wait . . . so on our surface is the streptavidin.
>
> No. 2 (Chemist): Actually . . . amines tend to be blue . . . so I'm gonna change that . . . at least on computer programs that I've worked with.

3.3 Erasing

We also looked for evidence of decision-making in their drawing actions, particularly around erasing. Surprisingly, in our entire experiment, a total of 43 erasing events occurred over the three prompts. The apparent purpose of these erasures was distributed equally across three major categories. Some erasures suggested changes in the participant's comprehension of the prompt. These were often accompanied by think-aloud commentary, "Oops, I did that wrong." (When a participant realized component A should have been above rather than below component B.) This type of change accounted for 14 of the erasures (32.6%). Editing-type erasures accounted for another 15 (34.9%). These, we classified as low impact erasures—included changing color to match their mental models. Finally, the remaining third of erasures

CHEMISTRY	ELECTRICAL ENGINEERING	BIOENGINEERING
Appearance of...		
▲ **Ligand appearance**	▲ **p- and n-type labels**	▲ **Labelling strategy**
▲ **Photoexcitation**	▲ **Silicon base**	Biotin
Molecular-scale view	▲ **Electrodes**	Step-by-steps shown
Lab-scale view	Nanotube appearance	Dilution
Excitation light	Potassium vs PMMA layers	Cy5
Electroexcitation		Antibody (GAR)
Luminescence		Antigen
Data plot use		Streptavidin
		DNA
		Consistent color use
Accuracy of...		
▲ **Ligand exchange**	▲ **Nanotube**	▲ **Serial Dilution**
▲ **Electroluminescence (EL)**	Electrodes	Biotin
Photoluminescence (PL)	Dielectric Layer	Cy5
Quantum dot	K+ doping	Detection scheme
Functional group	PMMA layer	Antibody
Separated PL and EL		Streptavidin
Time dependence study		DNA
		Antigen
		Method 1
		Method 2
		Method 3

Fig. 3. List of drawing components from each prompt. Components found to vary significantly by discipline are emboldened and marked by a solid triangle.

were those that dramatically changed the representation of a component (~36% came from one participant). A more detailed description of the categories is provided in Appendix B.

3.4 *Interviews*

We asked the participants a series of questions, which were tailored to their disciplinary background. For example, for an electrical engineer, we first asked:

> Imagine you have a chemistry background instead of an electrical engineering background. Do you think you would draw the same, or different?

Then we asked them how they might alter it for a different (similar) disciplinary audience:

> Suppose you are showing this [drawing] to an audience of all chemists (electrical engineers). Would you draw it the same or different?

Though our questions asked how their *drawings* would be different, nearly all the participants speculated on how they would re-tailor their *oral presentation* of the drawing. Categories like "Information content" and adjusting the "Amount of detail" featured prominently in the answers to these questions. When asked to imagine themselves with a disciplinary identity that matched the prompt (e.g. imagine you are a chemist for the chemistry prompt), many thought their increased knowledge would be reflected in the drawings by adding in more detail.

> No. 1: Okay. If I were a chemist, I probably would have drawn this [pointing to the test tube] much more detailed. Because I know what kind of reactions I probably need to do.
>
> No. 2: I don't know if that would've been as familiar . . . um, but . . . they have basic chemistry background, it would make sense, so it might not have been as detailed on that side . . . I could've made that more detailed, but . . .
>
> No. 3: But I think that an electrical engineer would focus more on the, yeah, on this like readout and detection, especially electroluminescence. Um, and maybe instead of drawing a box, they would draw what's actually going on there.

Most of these responses show that the graduate students were more concerned with number of "details", in the sense of the quantity of the information to be communicated. This is consistent with what we observed with the disciplinary trends: if the participant knew the chemical formula, it was drawn.

We also heard comments that showed some concerns with disciplinary identity, knowledge and interest. We see participants acknowledge their own disciplinary identity, but at the same time, feel that they have had non-traditional experience that distinguish them from more "traditional" researchers in their field.

No. 4 (Chemist): So, yeah, I'm a chemist, but I've got a little bit of uh, uh . . . device engineering in me and a little bit of physics in me too so. . .

No. 5 (Electrical Engineer): The thing is in, at least the stuff I'm working on . . . I'm not an engineer, or, I am an engineer, but I'm looking so much at bio stuff that I kind of know that. I'm not sure that an actual engineer who has never worked with bio . . . stuff, biotechnology stuff could actually draw it. . . . But if I just talked with someone who is doing controls, they wouldn't be able to draw it at all. I don't think they would get it. I mean I get it, so. They probably will get it, too.

At the same time, participants found it difficult to gauge the level of knowledge and interest they could expect from an audience outside of their discipline.

No. 6: I have sort of no grasp at all whether or not an electrical engineer would have a good idea of what fluorescence is. Like physically what it is. I know it's something that, as chemists we have, uh, we learn a lot about in our coursework.

No. 7: If I were learning this from someone as a chemist, I would be a lot more interested in getting more detailed than just a triangle with a notch and learning exactly how this interaction [works]

Notably no one explicitly suggested that the visuals could aid in bridging disciplinary or knowledge gaps, a range of representations for the same object exists in our experiment as well as in the literature [35].

4. Discussion

The revelation that there was no strong correlation between disciplinary training and graphical representations as observed either by *accuracy* of graphical representation or *appearance* has implications. This raises interesting questions pertaining to an implicit impact of interdisciplinary training that we had not noticed before. Could it be that nanotechnology education has an influence on disciplinary training? Indeed this observation could have implications for teachers and learners in all areas of science, and particularly in nanoscience and nanotechnology where cross-discipline connections are essential to advancing the field. Further, these findings align with, and shed more light on, previous work, which establishes that visual representation is not explicitly taught to students [36], and scholars who state that students often learn visual communication from their laboratory peers in a rather haphazard and self-directed way. For the most part, an individual's ability to create visual representations for cross-disciplinary science communication is shaped by one's exposure to a topic, and often by exposure to journal articles containing other researchers' representations. While this peer-to-peer exposure can be effective, there is an inherent danger of a 'ceiling' effect, since the learning is dependent on a variable that might not be adequate for the task and can often be decidedly inadequate [37].

In our analysis, many other issues surfaced as well in relation to scientists' abilities to communicate effectively using graphical representations. The action of creating visual representations, appears to be fraught with preconceptions and surface-level cognitive inventions [38–40], while deep reflection and metacognitive processes—attributes that many educators maintain are indispensable in this arena, [e.g., 41, 42] appear to be non-existent or minimally in use. Participants in this study rarely commented on ways to visually present their material—as if it was not something that ever occurred to them. When we asked participants to tailor their drawings for communication with different audiences, their responses demonstrated gross inability to grasp the significance of this topic.

For nanoscale related research, it appears that the process is not one that is heavily influenced by discipline-based background knowledge. Bluntly put, the participants in this study did not show much conscious thought that drawings and representations might be different to what was delivered for completing the task at hand. This is understandable *while* one is processing new information but, on reflection, and when asked specifically to explain, the absence of a focus on visual presentation rather than overall oral presentation is telling. We presume that specific attention paid to: 1) exposing students to researchers in other disciplines, 2) teaching visual design strategies for variations in visual representation, and 3) sharing strategies to address audiences of different backgrounds, would introduce significant impact in this arena. Future research should investigate the impact of generating metacognitive and reflective processes in students by focusing on visual design for any field, particularly those that require communication across disciplines that might be improved. Such improvements would go a long way to solving some of the inherent and flagrant shortcomings in the field concerning cross-disciplinary communication using visuals. When *ACS Nano,* Editor-in-Chief Weiss described the importance of "illustrat[ing] the dominant phenomena that rule the Nano scale world," he was speaking for a large population of scientists from many disciplines who understand at an intuitive level the graphical representation problem [40]. And yet there are significant hurdles for teachers, learners and engineers in this arena. Kindfield summarizes their issues by concluding that increased facility in producing and using an array of visual representations paves the way for deeper understanding of the science behind the representation [35].

By encapsulating scientific observations into a reproducible form—imaged, plotted or schematized—researchers have the ability to transfer newly discovered information to peers and beyond [43]. Communication is essential to scientific progress and as Yates avers, "un-communicated science in essence does not exist" [44]. Indeed, the scientific literature pertaining to nanotechnology contains many articles that point out the need for improved graphics [4, 44–47]. As this study shows, graphical communication is not necessarily easy but, we suggest that mindful creation of visuals for the purpose of communicating to both colleagues and learners is beneficial in multidisciplinary areas such as nanoscale research, as well as across science and engineering disciplines.

4.1 Limitations

While limitations associated with this study constrains us from making generalizable claims to a greater population beyond the small sample pool ($N = 16$) and source in evidence at the University of Washington, we think that the trends described in the findings establish a currency for deeper questions in this arena. We suggest that future iterations of this work would encounter a larger overall sample with the aim of replicating the findings and making those generalizations. Other limitations include the fact that variables associated with subject bias with "think-aloud" protocols are difficult to eliminate and might impact (negatively or positively) the final outcomes. Individual differences in social research can confound findings so that it is difficult to make claims that are generalizable beyond the sample under investigation. Nevertheless, trends and directions become visible in adaptations of studies where variables and individual differences are more or less contained.

5. Conclusions

In this paper, we presented results from a pilot study of visual communication in nanoscience and nanotechnology research. We investigated the impact of disciplinary training on visual communication for graduate student researchers in nanoscience and nanotechnology. The participants were a convenient selection of graduate students in science fields who typically use graphical representation in their work and presentations. The study drew on an analysis of participants' graphical depictions based on hand-drawn representations of previously published nano scale research experiments. Data consisted of video capture and participant interviews along with artifacts and drawings. Our analysis of these data suggests that there is very little correlation between disciplinary science courses and a student's ability to interpret a wider knowledge field as in nanotechnology and nanoscience. According to this study, science graduate students are predominantly successful at depicting high-level scientific concepts in and across scientific disciplines, but indicate that disciplinary boundaries arise at a topic-specific detail level. In the case of high-level conceptual components, less than a quarter of study participants had significant correlations with their disciplinary training. In other words, patterns of detail expression were not exclusive to participant discipline. We suggest that these findings might indicate that graduate students gain knowledge of areas of science not particularly specific to their stated discipline by being exposed to nanoscale research through nondiscipline-specific routes.

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7. Appendix A: Prompts

Prompt A (Warm up)

Draw a figure illustrating an aspect of your research (whether it works or not). It can be a process, a structure or an effect. Include as much information as you can.

Prompt B (Chemistry)

The researcher would like to test the effects of surface functionalization on the luminescence of CdSe quantum dots. She plans to perform a ligand exchange on a batch of CdSe quantum dots, exchanging the original alkyl amines on the surface with alkane thiols. The photo- and electroluminescences of the original and modified batches will be compared over time. The quantum dot photoluminescence is stimulated via a 532 nm laser; the electroluminescence is studied at a bias of 10 V. Draw this procedure.

Reference: [29, 30]

Key concepts: quantum dots; surface effects on physical properties; ligands; self-assembled monolayers; functional groups; lasers; light detection; photoluminescence; electroluminescence; potential difference/bias

Prompt C (Electrical engineering)

A p-n junction is built on a single molecule by modulating the doping of a single carbon nanotube. A single-walled nanotube (SWNT) is grown between two electrodes (one Ni, one Au), on a 500-nm thick silicon dioxide layer atop a silicon back gate. Half of the SWNT is covered by a 340-nm thick layer of poly methyl methacrylate (p-type), and the other half is doped with potassium by vacuum layer deposition (n-type). Draw this device.

Reference: [32]

Key concepts: devices; p-n junction; p-type/n-type materials; doping; masking; single-walled carbon nanotubes; single molecule manipulation

Prompt D (Bioengineering)

A research group compares different methods of preparing a biosensor by comparing the efficiency and specificity by which goat anti-rabbit IgG (GAR) antibody binds to a surface via three different methods. In the first, the antibody is directly spotted on the surface. In the second, the substrate is activated by covalently bound streptavidin to affix the biotinylated antibody. In the third, a short single-stranded DNA (ssDNA) is bound to the surface, where it is then incubated with a complementary, streptavidin-conjugated strand of ssDNA. The biotinylated antibody is then bound to the streptavidin. To evaluate the effectiveness of each attachment method, serially diluted amounts of the rabbit IgG antigen were exposed to the immobilized antibodies. Cy5-labeled GAR antibodies were then used to fluorescently detect the presence of the rabbit IgG antigen. Draw the three different methods of substrate preparation, and show how the different methods were evaluated for attachment density.

Prompt D (Bioengineering) Revised for Experiment 2

A research group aims to improve the attachment density of rabbit IgG antigen using biomolecular self-assembly. They functionalize substrates with goat-anti-rabbit IgG antibodies by an experimental and control method. For the control substrates, the antibodies are directly spotted onto the surface. The experimental substrates are built up in several layers. First, single-stranded DNA (ssDNA) oligomers are attached to the substrate. Second, complementary streptavidin-conjugated ssDNA oligomers are incubated with the surface ssDNA. Finally, biotinylated anti-rabbit IgG antibodies are attached to the streptavidin. The group then incubates the substrates with serially diluted amounts of rabbit IgG antigen. Cy5-labeled anti-rabbit IgG antibodies are used to fluorescently detect the presence of the antigen. Draw the preparation methods for both control and experimental substrates and show the method of evaluating attachment density.

Reference: [31]

Key concepts: biosensor; streptavidin-biotin binding; DNA hybridization; antibody-antigen binding; fluorescence; bio-molecule self-assembly; dilution assays; surface binding kinematics

8. Appendix B

Drawings

As described earlier, we used "appearance" (what did it look like) and "accuracy" (did it make sense) as a visual coding system, to classify 45 different aspects of participants' drawings from all prompts. We examined individual components as well as characteristics of the overall drawing. A wide range of representations was drawn by participants for each component: we will show a few representative examples here to illuminate our method. These examples have been isolated from the original drawings to show the individual components.

In the bioengineering prompt, DNA is used as a building block for molecular assembly. Figure 4 shows a representative range of the ways in which our participants chose to depict DNA:

The drawings are arranged by amount of detail contained, increasing from left to right. On the far left, DNA is pictured as an amorphous blob on the surface (a). The second drawing (b) breaks the layer into individual DNA "particles", and 3c shows not only individual molecules, but that each one has a helix-type structure. More detail can add to the amount of information conveyed by the visual, but detail that is incorrect takes away from the accuracy of the representation. For example, Fig. 4(e) shows the base pair "rungs", but also shows DNA laying down on the substrate, which is not consistent with the way DNA was used in the research. Figure 4(e) also omits the helical structure of hybridized DNA, which is sometimes used to draw attention to the base sequences. Even though accuracy and detail are interdependent qualities—good accuracy is impossible without sufficient detail—we split the coding systems to analyze patterns of appearance and

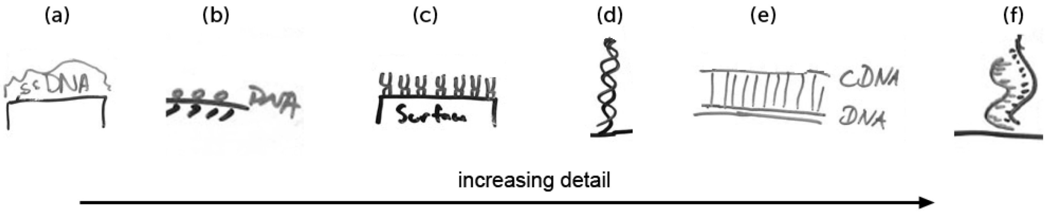

Fig. 4. Examples of DNA drawn in experiment. The amount of detail increases from (a) to (f).

accuracy. At the same time, detail is often purposefully exchanged for clarity in visuals; the choice is made by the individual scientist.

In the same prompt, participants read that antibodies were ''spotted on the surface'', that is, attached by exposing them to a substrate. Variations of the antibody representations are shown in Fig. 5, arranged so the amount of detail (and thus, information) roughly increases from left to right, and accuracy roughly increases from bottom to top.

As in the representations of DNA, the participants' drawings have a spread in both degrees of detail depicted and of detail accuracy. These representations all convey the idea of antibodies on a substrate, so for that purpose, none can be labeled as an *incorrect* representation, though some are *insufficient*. These anomalies in response from one short phrase show both differences in the participants' prior knowledge as well as stylistic and informational choices made in creating a representation.

Specifically, the participants differed in the amount of detail they chose to put into the individual antibody, as well as representing information on orientation(s) of the antibody relative to the surface. On the far left, we see no shapes, simply the letters ''GAR'' (for Goat-Anti-Rabbit) to represent the antibody attached to the surface. With the rest of the drawings, the participants used different shapes to represent the antibody, but only the top row of drawings (Fig. 5(b), (c), (d)) used an asymmetric shape to convey a random distribution of antibody orientations on the surface. The two right columns (Fig. 5(c), (d), (f), (g), (i), (j)) use a Y-shaped representation, conventionally used as it mirrors the underlying structure of an antibody molecule. The ones on the far right go one step further to show some more structure within the Y-shape. In all but (a) and (e), the participants chose asymmetric shapes that also convey differences in the orientation of the antibody on the surface. We see arrays where the antibodies are identically arranged (h, i, g, j) and those with random orientations (b, c, d, f).

Figure 6 shows the range of representations of a ligand on a quantum dot, drawn for the chemistry-based prompt. The ligands, in the context of the prompt, are the molecules that are bound to (and thus, ''hang off'') the surface of the semiconductor quantum dot. The prompt specified that the ligands used were alkyl amines and alkane thiols: arbitrary length carbon chains that end in either a nitrogen or sulfur, respectively.

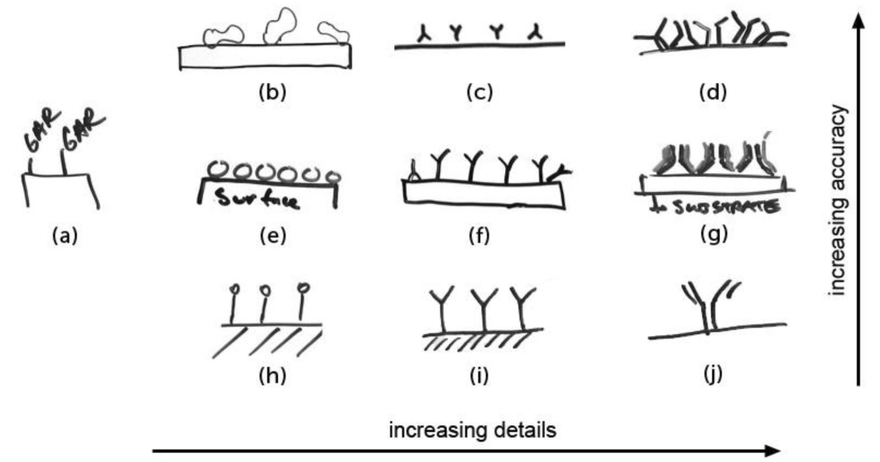

Fig. 5. Examples of antibodies as drawn in experiment.

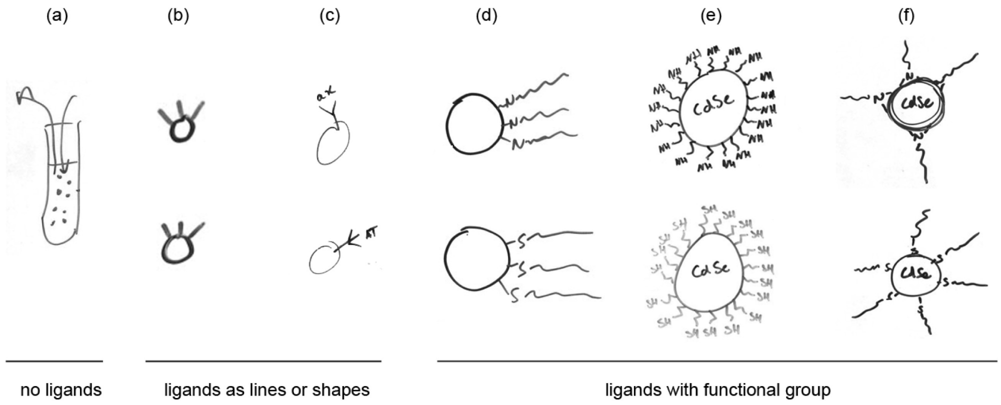

Fig. 6. Examples of the two different ligands on quantum dots as drawn in experiment. Top row are quantum dots with alkyl amines, bottom row are with alkane thiols.

The range of representations here, as we move from left to right, evolve from no representation (the quantum dots are shown), to a depiction that includes the chemical structure of the ligands. Clearly, more prior knowledge is needed by the participant to produce the detailed drawings on the right ((d)–(f)), but a simpler drawing like ((b), (c)) could also have been drawn by a participant with similar knowledge that chose to visually simplify information for clarity.

9. Appendix C

Drawing revisions

Transcriptions of the session (which included participant actions such as erasing) were searched for occurrences where the participant erased by using their hand or eraser. None "marked out" instead of erasing. These erasings were categorized into five apparent motivations, based upon the observed result of the revision and their think-aloud verbalizations:

1. Revising to reflect increased comprehension/understanding of the prompt
   For example, reordering two components, "I got that wrong the first time."
2. Changing the representation of a component
   Redrawing any or all of a drawing for a different shape or perspective; a conscious revision more significant than a color change or line-modification.
3. Minor revisions
   a. Restoring visual consistency (with themselves)
      "Hmm... I should make it look more like the other one." (X03—pD) This change looks visibly different before and after; similar to Motivation No. 2 except it is to correct unwanted variation
   b. Color changes
      Redrawing looks indistinguishable original drawing, but just a different marker color.
   c. Correcting handwork: rewriting text to make more legible, redrawing lines that came out differently than intended
      Nearly automatic corrections due to the hands-on nature of the experiment: Ex. Correcting misspellings, drawing . . . the resulting drawing or writing looks indistinguishable from original (they noticed something we didn't).

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