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Grounding Scientific Inquiry and Knowledge in Situated Cognition

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Abstract

We used ethnographic methods to study the cognitive processes and the social environment in an organic synthesis laboratory for its particular kind of human problem solving in scientific discovery (Klahr & Simon, 1999). Current work in situated cognition fills the fissure between problems posed by psychologists, both cognitive and behavioral, which have tended to focus on individual learning and learning of academic tasks, and the problems posed by sociologists of science who examine social influences on knowledge production within organizations. Further, Greeno (1998) asserts that the situative perspective, as it examines intact activity systems, can provide a synthesis that subsumes the cognitive and behaviorist perspectives on learning. We hypothesized that a research laboratory follows the literature conceptions of situated learning in terms of communities of practice, cognitive apprenticeship, scaffolded learning, affordances, constraints, and the production of valued knowledge and other products via a social epistemology. We found that researchers adapted their reasoning to performing effective organic synthesis research, which is an attuning process in a type of cognitive apprenticeship. The researchers were guided and constrained in their reasoning by the organic research community's practices utilizing particular objects and processes. Aspects of any problem to solve attuned them to perception of new affordances, thus stimulating learning in emergent intention and attention. Each field in science has different things to reason about, different consequences to gauge, and thus, different criteria for justifying the conclusions drawn (Toulmin, 1977). We conclude that the thinking and acting occurring over time by apprentice researchers in the organic COP molded everyday thinking into the scientific reasoning required to be "certified" in this field as a research scientist.

Recent work in situated cognition fills the gap between (a) the problems posed by psychologists that have tended to focus on individual learning and learning of academic tasks, and (b) the problems posed by sociologists of science who examine social influences on knowledge production within organizations. Situated cognition examines how humans learn, remember, and understand as a result of sense making that occurs from physical and mental interactions with the objects and events of an everyday setting (Lave & Wenger, 1991); that is, the learning that develops in close relationship to doing. Our study explores a research group performing organic synthesis of novel molecules. We are interested in

the way graduate researchers' thinking and learning (cognitive processes) are influenced by the research environment as they learn how to carry out scientific inquiry, reason scientifically, and acquire scientific knowledge. We propose that the development of graduate researchers is a closer parallel to the learning of science students than studies of science as an institution.

We theorize that situated cognition is plausible and fruitful as a theoretical framework for understanding scientific reasoning and growth of scientific knowledge in day-to-day scientific inquiry; that is, that a research laboratory follows the literature conceptions of situated learning in terms of communities of practice, cognitive apprenticeship, scaffolded learning, affordances, constraints, and the production of valued products, through a social epistemology.

Situated Cognition

There is now more recognition within science studies that researchers learn as they are immersed in a world of people, environments, and objects (Gooding, 1992). Participants must adapt, reflect, judge, compare and make seemingly appropriate decisions (Clancey, 1997) from the work and concrete interactions within a meaningful social setting. Therefore, conditions for situated learning concern (a) the level of concrete interactions of individuals who act in a meaningful social environment, and (b) transactional relationships composed of back and forth interactions with environmental resources, tools, people, and constraints to carry out daily tasks. Theories of situated experience focus on agency and intentions of people, existing on a day-to-day basis within the community. Situated experience requires coordination with others and with activities; it requires improvisation; it requires negotiation through interactions and flexible change; it builds identity for the group and its members.

Practices and Epistemology

Historically, people interact and work collectively for particular goals. In doing so, they develop practices (Wenger, 1998). In *Cognition in the Wild* Hutchins (1995) describes Navy navigation as it is done on the bridge of a ship as, "human cognition in its natural habitat—that is culturally constituted human activity" (p. xiii). Hutchins

interprets the cognition required for navigational prowess in terms of a system of practices that have evolved over centuries. In summary, tools and practices develop within the framework of situated work on a problem. A particular use of a tool is a simple example of a social practice.

Practices are actions of members of a community who are accomplishing valued work there. Practices require knowing as well as doing. Practice occurs because there is work to be done, e.g., “relationships worked out, processes invented, situations interpreted, artifacts produced, conflicts resolved” (Wenger, 1998, p. 49). The community participation is not simple. As the community is mutually engaged, the work itself requires analysis, evaluation, negotiation, dissent, justification, as well as incorporating others’ points of view.

Epistemology evaluates intellectual practices that produce knowledge, according to Goldman (1998). Further, social epistemology evaluates social practices that produce knowledge, he says. The epistemology of situated learning depends on knowledge production and distribution in social processes and interactions. Cognition, therefore, is understood to encompass the interactions between agents and environment, not simply the potential representations and processes in the head of a participant. Reasoning is distributed among workers who utilize a specific tool’s knowledge, for example. Nersessian, Kurz-Milcke, Newstetter, & Davies (2003) have written about the biomedical engineering research laboratories as “evolving distributed cognitive systems in which the environment provides the rich structure that continues to evolve to support emergent problem solving.

Goldman (1999) explains that social epistemology depends on how, when, and by whom new knowledge is transmitted to others. This is in contrast to an individual epistemology, which focuses on “the mental operations of individual cognitive agents in isolation or abstraction” (p. 4). He classified the following three social dimensions of distributing knowledge (p. 4): (a) Social paths or routes to knowledge, (b) Social groups made of knowing individuals, and (c) A collective group as a potential knowing agent.

Social routes to knowledge are composed of interactions with other agents in a kind of specialized location. We propose that apprenticeship is the social route to knowledge in which a novice spends time with experts to learn a highly skilled profession. Since an apprentice is immersed in a situation in which knowledgeable others are also working to produce similar types of products, situated learners are in a proficient environment where expertise is commonly seen. Apprenticeship is a socialization process in which the novice learns from implicit modeling and explicit guidance of more experienced others to master valuable skills, which produce significant products. Cognitive apprenticeship gradually leads the researcher into more of the central practices as well as to creating more of the community’s products. Finally, in a cognitive apprenticeship, researchers become sensitized to the specialized and detailed conditions of activity in the community designed for particular purposes.

A social group of knowing individuals. We put forward that a specific research laboratory is a production-based community of practice (COP) in which scientific knowledge is generated, thus making the research group an epistemic culture. For a common understanding of lab work, we will use Clarke's (1997) breakdown of work organization from her grounded theory work. “Production-based social world” described scientific research, other scholarly work, or the commercial enterprises of manufacturing and industry, all based on activities that produce something. A *line of work* in science is “all activities that address a given set of coherent and cohesive problems” (Clarke, 1997, p. 72). A line of research is broken down into several programs of research to address a group of related questions, and which usually use a characteristic set of techniques, equipment and instrumentation. Each research program is separated into a set of related projects having shorter-term goals that lead in the direction advocated by the program. A project is often the work of one researcher while fellow researchers are involved in interrelated projects. Clarke describes projects as composed of activities (experiment or experimental system). Activities mature through completed tasks or some improvisation of the task that enable the experiment to work.

Wenger (1998) specified three commonalities among COPs. One commonality is mutual engagement, which hinges on the purpose of what COP members are supposed to accomplish, which is the joint enterprise. They learn in joint connection with each other how to accomplish the joint enterprise as they continue to work in achieving those goals, implying that learning emerges throughout work. Since each COP has, as its enterprise, particular types of research programs, each COP has its own shared repertoire of standardized procedures to tackle research programs. Each COP has its own infrastructure dedicated to its own-shared repertoire of standardized practices.

A collective group as a potential knowing agent.

Goldman (1999) classifies the third arena of social epistemology as collective or corporate entities, such as juries, which are capable of knowing. In science we propose that these are a research field. The knowing collective research field is the group of COPs, each using similar practices. Research fields are capable of “selecting the social practices that would most advance the cause of knowledge” (p. 4). Notice Goldman’s emphasis on the practices rather than the knowledge per se. If COPs hold practices in common, then their communication can be fluent and global. Star (1999) found that important practices are fairly coherent across local sites and different communities. They create the common denominators for comparisons and contrasts in knowledge. Infrastructure is the feature that enables and stabilizes efficient and flexible utilization of important practices.

According to Goldman (1999), justification of social practices is the result of strategic distribution of knowledge and reasoning where they are socially transmitted in a

series of four social processes leading to an accepted knowledge claim: discovery; message production and transmission (distribution); message reception; and message acceptance (as in peer review). Absolute objectivity would imply that all standards for justification will be the same (Megill, 1991), but justification in science is reliant on its material, intellectual, and social contexts, and thus discipline-based requiring different criteria for justifying the conclusions drawn (Toulmin, 1977; Megill, 1991; Goldman, 1999). Therefore, the investigation of the field of organic synthesis requires that we look for the manner in which specific types of justificatory reasoning are communicated in this research field.

Constraints and Affordances on Reasoning

Greeno (1998) points out that a substitute for model simulation to explain aspects of activities is using an attunement of constraints and affordances, to explain activities. 'To constrain' has many connotations Particular norms, practices, and other emphases constrain by affecting reasoning and actions in the following possible connotations:

- Limit, bound, set parameters
- Frame, define, require, propose conditions, set criteria
- Moderate, regulate, judge, keep within limits or bounds
- Emphasize, leave none or few alternatives

Constraints are regularities in social practices and interactions that affect reasoning and actions associated with the community's participants, objects, and processes.

Affordances for reasoning are those aspects of an environmental system (objects, processes, people, etc.) that an individual or group of individuals recognizes and utilizes to reach the current goal (Gibson, 1977). The infrastructure provides a large proportion of the affordances, as do scaffolding practices. The individual researcher, or in league with a mentor, learns to perceive and utilize it to reach a current goal--which may be continuing progress or solving an emergent problem. Gibson's definition specifies that a complementary relationship exists between the person and the resource. In order to be a true affordance the person must perceive it as relevant and then utilize the resource. Young et al. (2002) explain the learning process as explicit attunement of attention. A new attentional focus leads to appraisal of unutilized resources that fit the new situation. So tuned attention prompts a resultant intention to do something new. A new action further prompts attentional cues.

Methodology

This ethnographic study took place in an organic synthesis laboratory at a large, research I university. We use methods endorsed both by the psychology and sociology of science, based on ethnography. Klahr & Simon (1999) described and critiqued complementary methods to study discovery in science by specifying how ordinary cognitive processes

enable humans to generate the hallmarks of science, in which they quote Einstein saying were (a) precise definitions, (b) systematic choice of experimental material, and (c) logical economy (in terms of reasoning with domain-specific representations). Our methodology is the observation of daily work and problem solving in organic synthesis laboratories as others have done in biomechanical engineering (Nersessian et al., 2003) and molecular biology (Dunbar, 1995). Ethnography is a more time-consuming approach, Klahr and Simon noted, but they gave it high marks for face validity, construct validity, short and fine-grained temporal resolution, ability to find new phenomena, high rigor and precision, and capable of explicating social and motivational factors (p. 8).

The research environment is composed of four laboratories and one computer office. This particular chemistry research group contained participants of varying levels of expertise. Arnold Hjelle (a pseudonym) is the research director and a chemistry professor. The majority of researchers (10) are graduate students while three are postdoctoral and three are undergraduate researchers. Over 100 hours of video data were collected, including footage of researchers working in the research lab, gathering and interpreting data, interacting with peers and mentors, and attending weekly group meetings. Informal and semi-structured interviews, detailed field notes collected by the field researcher, copies of laboratory notebook pages, and copies of experimental evidence were collected.

Results and Discussion

Infrastructure

Each research COP designates the physical spatial boundaries, organization of individual and group space, and the type and use of materials and equipment. The support for practices is the infrastructure and is commonplace to the workers.

We simplified the three basic ontological categories of entities, processes, and mental states that psychological linguists have identified (Keil, 1989). We placed all animate, inanimate, visible substances and artifacts, including humans, under the heading of Object (Bond-Robinson & Stucky, submitted). Subcategories are given in Table 1. We placed all processes, including chemical and physical, human actions and mental states (emotions and ideas) under the category of Process as seen in Table 2. Scientific concepts are theoretical objects, which are created as tools to conceptualize a character and name, e.g., atoms, electricity, and mass (Blumer, 1931). Theoretical explanations are seemingly appropriate organizations of theoretical concepts. Scientific representations include unique ways of illustrating concepts and processes.

Table 1: Objects Found in the Laboratory

ARTIFACT	VISIBLE SUBSTANCE	HUMAN	THEORETICAL OBJECT
Environmental structure	Chemicals by function	Research Group	Atoms, molecules, ions
Space planning	Substrates	Scientific Public	Molecular structures
Fume hoods	Reagents	Individual Researcher	Chemical symbols
Lines of Research	Solvents	Research Director	Charge; polarity
Projects, Activities	Atmospheres	Graduate Researcher	Functional groups
Environmental resources	States of Matter	Post doctoral researcher	Molecular agents
Equipment	Solids	Undergraduate researcher	
Instruments	Liquids	Mentee, relative novice	
Scientific Products: Data	Gases	Mentor, relative expert	

Table 2: Processes Found in the Laboratory

CHEMICAL & PHYSICAL	HUMAN ACTION	MENTAL STATE	THEORETICAL EXPLANATION
Synthesis	MECHANICAL WORK	CONSCIOUS	Organic reaction mechanisms
Reactions	<u>Researcher-built system</u>	Frustration	Functions of molecular groups
Solubility	1. Troubleshoot mechanical sys.	Having a goal	Functions of acids and bases
Bonding, Intra- & Intermolecular	2. Feedback of mechanical sys	Having a problem	Most data interpretation
Procedures, e.g.,	3. Interpret mechanical data	Metacognition	
General Synthesis	<u>Instrument system purchased</u>	Explicit reasoning	
Separations	2. Feedback of mechanical sys	Mechanical reasoning	
Identifications	3. Interpret instrument's data	UNCONCIOUS	
	MENTORING	Implicit learning	
	Nested apprenticeship	Tacit knowledge	
	Group Meeting		

The COP's Joint Enterprise

This group's goal is to engineer novel organic molecules that should possess particular kinds of medicinal properties. The basic structure of organic molecules is a carbon chain. In the simplest molecule there is only one carbon atom, CH₄ (called methane), and it is bonded to four hydrogen atoms. Large organic molecules have more carbon atoms, each bonded to other carbon atoms on either side and two hydrogen atoms. Other kinds of atoms or a group of atoms bonded together can substitute for a hydrogen atom. When an oxygen atom, -O-, or sulfur atom, -S-, or a group of atoms (such as -NO₂) pushes out a hydrogen atom to take its place in the molecule, such a substitution reaction alters molecular structure and resulting function. Hydrogen atoms can also be removed from somewhere within a chain of carbons, creating C=C, a carbon-to-carbon double bond, in that location. Researchers engineer novel organic molecules by adding or subtracting functional groups in organic reactions. In strategic chemical reactions they add or remove a functional group selectively, i.e., removed from one or two places on a molecule rather than all the positions occupied by that functional group. They can use 'recipes' found from the literature, called literature preps, which describe reactions yielding similar molecules. Members of the group attempt to optimize a wide range of variables such as reagents, temperature, solvent, and catalyst to prepare the

desired molecule efficiently and gain insights into the processes upon which further decisions can be based. The project begins from a basic starting molecule until the engineered molecular goal, with its specific and valuable medicinal properties, is indubitably synthesized (i.e., instrument feedback is interpreted and then justified as the desired molecule). The major reaction technique in Hjelle's lab currently is a special kind of polymerization. It is a versatile and dependable reaction in which a catalyst breaks a small ringed hydrocarbon into the chain version of its structure, thus opening the ring. The catalyst is now attached to one end of the molecule; it reacts with another starting molecule and adds it to the chain.

Mutual engagement in the COP

Mutual engagement is supported by the COP's infrastructure of objects and processes. Infrastructure is rooted in common practices and stabilizes them. Visible substances were stocked. Shelves with safety lips hold bottles of starting materials, catalysts, and reagents. Cartridges of solvents such as hexane, methylene chloride and ethyl acetate are attached to the walls. Metal cabinets house amine and acidic compounds. Strategically placed gas cylinders contain species such as argon, hydrogen, helium, and air.

All researchers run reactions in their own fume hood. A fume hood is an enclosed workspace whose atmosphere is exhausted to the outside of the building. Toxic vapors generated inside the hood are captured before they enter the lab space. A glass sash is the sliding door that pulls down from the top of the hood. Glass sashes attained functionality as transparent “whiteboards” where structural formulas of reagents in reactions, reagent amounts, and reaction times and dates are written with markers.

Common equipment is stored around the workbenches. Prongs on the walls hold clean glassware, while dirty glassware sits in washtubs at the ends of workbenches. On the surface of workbenches lie analytical balances, ovens, rotary evaporators, heat lamps, and gas chromatography (GC) systems. Chromatography columns and separatory funnels used to purify reaction products are in use on workbenches and in fume hoods. Pipettes, ring stands, clamps, larger glassware and other tools and equipment used in this community are stored in drawers and cabinets beneath the workbench surface. Manuals and instructions for common procedures hang in transparent sheet protectors around the lab.

Instruments were proximally available in separate rooms or in communal instrument labs for all chemical researchers for example, Infrared (IR), Nuclear Magnetic Resonance (NMR) Mass Spectrometers, and an X-ray diffraction for revealing crystal structures.

Constraints support mutual engagement. The intention to meet hallmarks in a scientific culture doing organic synthesis leads to four necessary constraints. (a) Mastering objects and processes toward community goals is a necessity; (b) Working while aligning with the norms and standards of the COP; (c) Using and further developing mechanical reasoning, which is used to build systems for generating feedback and evidence to reach goals; and (d) expressing oneself fluently in the appropriate language of the COP.

Mechanical reasoning is a constraint. It is clear from our observations that constructing mechanical systems is essential in the science of organic synthesis. Mechanical reasoning is a key part of each practice in the repertoire

Using appropriate symbolic language is a constraint on reasoning. A necessary constraint is expressing scientific work in terms of the standard *symbolic language* of the community. Molecular structures written out in terms of elements and spatial correlations would be considered perceptual symbols to those initiated in the community. But an amodal symbol bears no resemblance to the object or phenomenon it represents, e.g., instrument feedback is amodal; the symbols must be interpreted before they represent chemical species.

Affordances support mutual engagement. Researchers are enabled in a specialized laboratory environment with sets of unique artifacts, substances, people, and theoretical concepts to facilitate production of significant research goals. Although basic practices to pursue lines of research and projects exist, the actual methods to reach new goals are adaptations and are not trouble free; consequently they require judgment and decision-

making. The work itself consists of chemical and mechanical processes facilitated by human actions, appropriate mental states, and theoretical explanations as community researchers make progress and solve problems on their project.

Progress, barriers, and anomalies are addressed publicly at the Group Meeting each week. Features of a problem that needs to be solved affect perception of environmental affordances, stimulating intention and attention. Circumventing or breaking barriers is essential. Weekly formal meetings provided opportunities for researchers to make suggestions to other researchers about their barriers and anomalies; and gain experience presenting their work to other researchers. Sally, a novice researcher comments that the action of preparing to present at the group meeting allowed her to see her project work in terms of the big picture and the gaps. The presenter described his/her reactions; reagents used, conditions applied, and report on methods used from the literature. Molecular species and structural representations to represent reagents and desired products of the reactions, were written on chalkboards all around the room for discussion. Each reaction was followed by a description of whether it did or did not work (e.g., no reaction, messy), the chemical structures and ratio of products in the resultant mixture). The group and research advisor discussed problems that arose, quickly but in detail. Consequently, opportunities for developing research strategies to fill identified gaps arose, so the researcher had some alternatives to try back in the lab. New attunement changes the researcher’s immediate intention, such as trying to put a system together in a different way.

Shared Repertoire of Standard COP Practices

The organic synthesis research group has its own set of norms, rules, and standards of action that are imposed by the synthesis community’s standards for performance and products. Fujimura (1997) defines standardized procedures as routinized and conventionalized procedures to reach valued goals. Standardized procedures are practices that members utilize again and again. The relationship of standardized practices to reasoning in a COP is a crucial one because the purpose and reward structure in a production-based COP is based on production of valued products. Ultimate valued products in organic synthesis are a new reagent to synthesis a target molecule and a less complex or less expensive procedure to accomplish valued work.

Numerous consistent procedures are used in the same way from organic lab to organic lab, thus stabilizing the knowledge gained from these methods. Standardized procedures exist for running reactions, separating desired molecules from a reaction mixture, and identification of the molecular product separated from the reaction mixture. Separation techniques include solvent removal, distillation, extraction, crystallization, filtration, and chromatography. Standard knowing exists for safe operation. Philip, a graduate researcher, summarized safety issues in the practices as knowing what you’re doing, knowing the reagents and what they can do to you, and knowing how reagents react with others.

Determining the identification of a produced molecule utilizes instrumentation. Instrumental practices incorporate disciplinary knowledge into their performance of separation and/or identification. They can be manufactured with high sensitivities for particular kinds of molecules. The resultant output data is often paper feedback that acts as evidence of synthesis of a particular molecule; it tells researchers if the reaction yielded the product they expected. Instrument feedback is amodal; the symbols must be interpreted before they represent chemical species. Compare the instrument's output data with the molecular structure that must be interpreted from it in Figure 1.

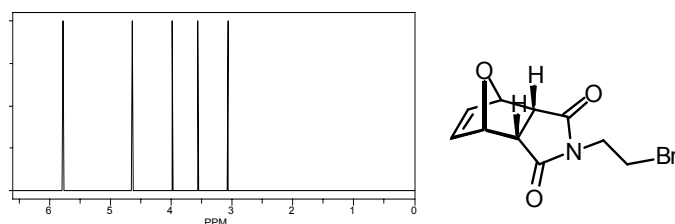


Figure 1

Conclusions

A successful researcher meets project goals or redefines them as a result of persistent effort over time, solving problems and finding out more about the fundamental nature of the research project. The graduate research experience is one where researchers are apprentices interacting to practice organic synthesis in a specialized laboratory. The prescribed activities were practices developed for the sustained pursuit of synthesis of novel organic compounds. Thus, organic research practice has developed standards, norms, and resources that define their concepts and explanations, gather materials and practices, and develop shared representations to communicate salient features efficiently and effectively. Constraints are the standards for work and normal behaviors that new researchers must emulate to be successful.

While not devaluing individual cognitive processing and personal behaviors, our study of scientific inquiry describes the daily kinds of interactions of researchers with objects and processes. Mentors are more experienced community members who provide scaffolding for novices as they are immersed in new practices. Practice is ungraded on an everyday basis in that researchers work to solve problems until they get the project to work. The learning environment in organic synthesis clearly models proficiency. The apprentice organic researchers were guided in their reasoning in a type of cognitive apprenticeship in which the researcher worked to complete many steps to a final goal in their projects (a project aligned with others in the same line of research); and they adapted reasoning in attuning to the constraints and affordances of organic synthesis research. Over time the community's ways of thinking and acting molded the everyday thinking of graduate students into the scientific thought required to be "certified" in this organic synthesis field as a research scientist. The theoretical understanding of daily scientific practice provides a vision of how learning actually develops in a situated community designed for specific purposes. We argue that aspects of a problem, which affect perception of

affordances in the community's environment, stimulate intention and attention. New attunement causes a change in the researcher's immediate intention, such as trying to put a system together in a different way. Situated scientific inquiry is then an education of intention and attention toward shared scientific goals in which researchers gain the sensitivity to become attuned, thus aligning their views of the molecular world.

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