

## CHAPTER 4: RESULTS AND DISCUSSION

### Research Design

The following questions were addressed in this study:

1. What are the distinguishing problem finding features of externally-evaluated, exemplary, open-inquiry science research projects?
2. How do parents, teachers, and mentors influence student problem finding?

The questions are answered through analyses of individual cases followed by a synthesis of all cases. Data were triangulated between student cases as well as using teacher and mentor interview cases, surveys, and documents. Multicase data analysis was focused around the following three themes: (a) problem finding and inquiry, (b) problem finding and creativity, and (c) problem finding and situated cognitive learning.

An overview of each student is provided, focusing on student demographics, student project problem finding, and student successes at science fairs. Pseudonyms have been assigned to each student and are positioned in alphabetical order. Students in this study participated in either the Connecticut Science Fair (CSF) or the International Science and Engineering Fair (ISEF). Summary tables for students, their project fields, and their fair results are found at the end of the CSF student profile and ISEF student profile sections. Entrance to the Connecticut Science Fair (CSF) and ultimately the International Science and Engineering Fair is by a systematic process as described in Figure 8. Non-Connecticut ISEF students who participated in this study followed a similar path as CSF students to gain ISEF admittance.

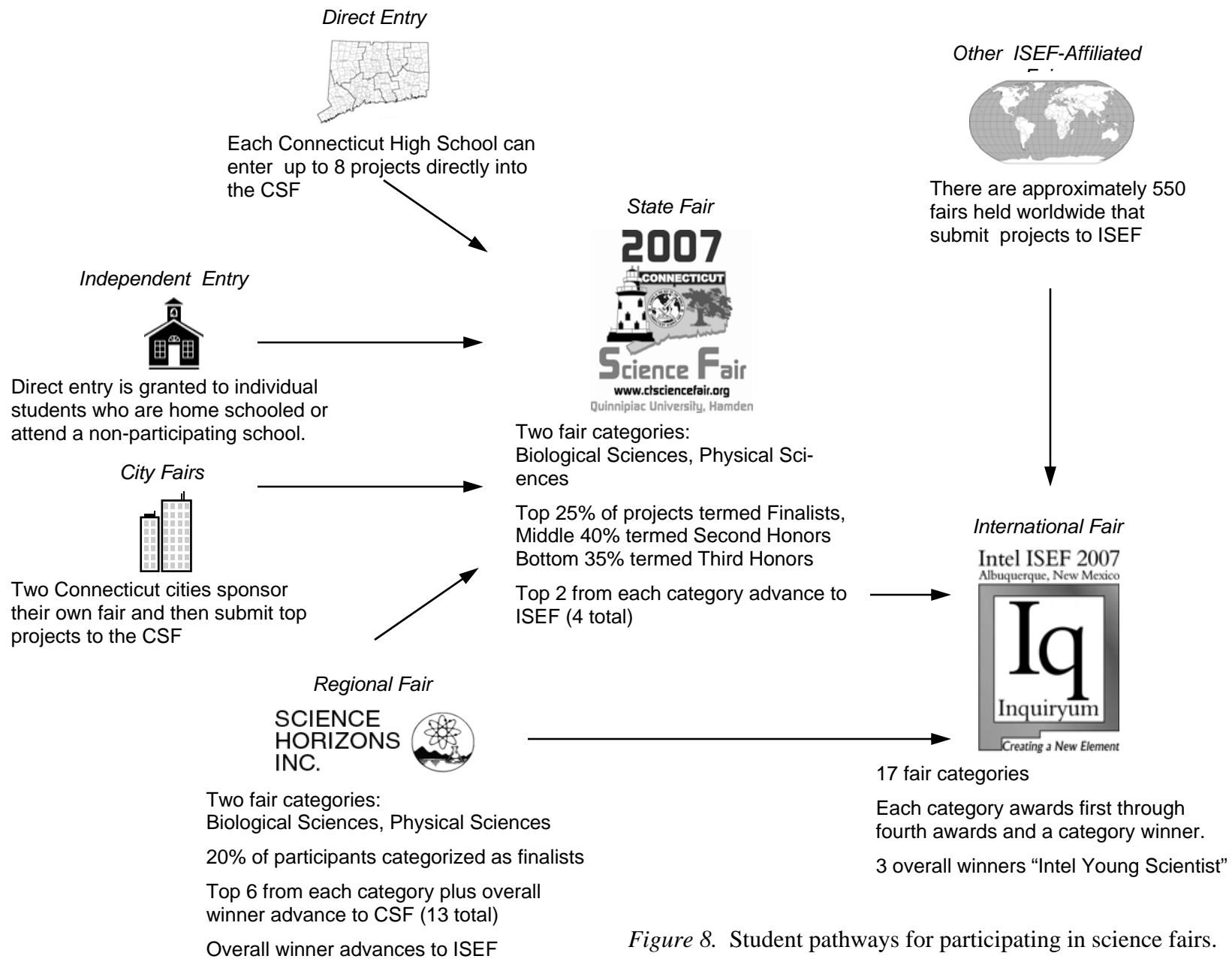


Figure 8. Student pathways for participating in science fairs.

## Connecticut Science Fair student profiles

### *Andrew*

Andrew is a 17-year-old senior, attending a public high school in an affluent coastal Connecticut town. He has participated in his school's formal science research program for three years, always focusing his research on his primary passion: computer science. He also has an interest in languages and has worked to integrate both in his research. In addition to taking his science research course, Andrew is enrolled in four Advanced Placement courses, including AP Calculus BC, AP Physics C, AP US Government, and AP Spanish Literature. He is also taking Middle East Studies and Contemporary American Literature.

While working on computer science-type projects, Andrew discovered an article on a computer news site that discussed a new algorithm that could analyze bodies of text. Recognizing the value of this algorithm, Andrew contacted the author and diligently persuaded the author to provide him with the source code. Andrew recognized the limitations to this algorithmic method and developed his own heuristic method. This heuristic method is a trial-and-error method of problem solving, used when an algorithmic approach is impractical (LPG, 2008). He used his experiences from science research, as well as AP Statistics, and an online linguistics course he had taken, to develop his problem and strategy.

Andrew presented the results of his computer science research for three consecutive years at the Connecticut Science Fair (CSF). Each year, he was a fair finalist, garnering awards tailored for the computer science subcategory. This year his project entitled, *A novel heuristic search method using inferential statistics*, finished fifth place in the physical sciences category, which is one of the two general fair categories. There are typically well over 100 entries in this category. He won first place in the math subcategory, third place in the computer science subcategory, and

received three special awards. Andrew's project was the design and implementation of a method for analyzing speech patterns, a sophisticated grammar checker. He used a unique algorithm to do the searching. He regards the projects he produced over the three years as one continuous process.

Andrew worked independently under the auspices of the school's science research program. His school's program director is a Ph.D. neurobiologist. Andrew utilized support, primarily via email with professors and researchers, but does not identify any one person as his mentor.

Andrew was also a national semifinalist in the Intel Science Talent Search, the country's oldest and most highly regarded pre-college science contest, designed specifically for seniors who have conducted independent research. Andrew plans on majoring in computer science in college. His experience in the science research program has focused and strengthened his interest for this field of study.

### *Bobby*

Bobby is an 18-year-old junior, attending a private high school in an upper-middle-class rural community in northwestern Connecticut. An exchange student from China, Bobby is boarding at the school and was also assigned a host family in the community. He regularly spends time with his supportive second family, but will be returning to China at the end of the academic year. Bobby's interests are in Chemistry: the focus of his project. Bobby is enrolled in AP Calculus BC, AP Chemistry, AP Music Theory, English, and United States History.

Bobby's project entailed the development of coating for paper that would allow it to be reused. The pen used water as ink; and the paper had a chemical coating that would react with the water to produce an image. After time, the watermarks would fade and disappear so the paper

could be reused. The basis of Bobby's project derived from his native land. He is a young man who is gravely concerned about the amount of forestry being cleared in China.

Bobby strived to develop a new type of paper, as no one had undertaken anything like this before. He did extensive research both online and in person. Visiting stores in China, he saw what kinds of products were already in existence. Bobby conducted almost all of his research and experimentation in China. Once Bobby had conceived of his general idea, he worked with his teacher and made contact with university professors to troubleshoot ideas for possible solutions. His main challenge was devising a strategy to utilize materials that would work in a very practical way. He was concerned with the seemingly endless approaches to the problem, and tried multiple strategies before finding a successful combination of chemicals to achieve his goal.

Once in the United States, Bobby elicited the help of teachers and fellow students to examine and evaluate his work. He evaluated their suggestions and incorporated those he felt would benefit the ultimate presentation of his work. His project, *The preparation of an environmentally friendly "novel paper" for painting and calligraphy exercises*, was presented both at the CSF and the Connecticut Junior Science and Humanities Symposium (CT-JSHS). His enthusiasm and excitement at both venues was contagious and he quickly surrounded himself with many new friends who were interested in both him and his project.

Bobby placed third in the physical sciences category in the fair, and won third place in the applied technology subcategory. After completing his senior year in China, Bobby hopes to pursue a college degree in chemistry. He has a deep appreciation for his experience in the United States.

## *Caitlin*

Caitlin is a 16-year-old junior attending a technology-based magnet school in a central Connecticut urban center. She was recruited to participate in her school's newly formed science research class. The research class was developed in conjunction with a regional educational resource center (RESC) using interdistrict funding, which seeks to develop interactions and collaborations with suburban and urban students. Besides her science research class, Caitlin is enrolled in SAT preparation class, A+ advance computer software course, and honors American literature.

Caitlin struggled immensely in the development of a project idea. Her teacher allowed her to go through the struggle independently, to Caitlin's regular frustration. She eventually developed a project related to tsunamis. However, because of the limitations associated with her ideas, she lacked a tangible original concept. Her project, therefore, was mainly based on preexisting data. She recognized that the project did not merit significant external recognition, but nonetheless identified her unwavering dedication to its completion.

Caitlin worked under the careful guiding mentorship of her teacher. Her project, *Designing future tsunami protection in the eyes of the coast lines*, was awarded third honors in the physical science category at the fair. That award placed her in the bottom third triad. She considers the award an honor because it represents her successful completion of a body of work. Having completed the science fair experience, Caitlin admits to valuing the frustrations associated with her project and its development, because she now knows she is able to accomplish a large meaningful task on her own, regardless of the challenges. Caitlin is considering attending college and would be the first member of her family to accomplish such a goal.

### *Dana*

Dana is a 16-year-old junior also attending a technology-based magnet school in a central Connecticut urban center. Dana was recommended for her school's science research class. In addition to science research, she is enrolled in SAT prep, pre-calculus, and honors English.

Dana decided that she really wanted to conduct a project that she perceived to be very practical. Observing that she was often tired during the school day, she decided to see if there was a solution to her exhaustion. Dana worked with her science research teacher and her gym teacher to conduct a study about the effects of a yoga program on students' alertness during the school day. Working with her fellow classmates as subjects, she coordinated a 1-week study with a control and treatment group, where each participant would self-report his or her alertness at various times during the school day. She clearly understood the limitations to her project and the inability to control confounding variables that might be present. She also generally used techniques of convenience while conducting the study.

Dana reports that the selection of her topic came easily – she did not spend much time thinking about it. She had some initial interest in sleep and noticed that there were quite a number of websites that mentioned yoga. When her gym teacher informed her that he was going to try a yoga program, she jumped at the idea.

The study, entitled *Does yoga influence a student's alertness during the school day?* was awarded third honors in the life sciences category of the CSF.

### *Eric*

Eric is a loquacious 17-year-old senior, attending a private academy in an affluent coastal Connecticut town. Eric's school does not have a formal research program, although his

chemistry teacher is interested in launching one. Eric's project was completed under the auspices of an independent study. Eric gave up taking a fourth year of language to take independent study in conjunction with another science class. Rejecting the counsel of others, he was advised against this path by a counselor and peers. They felt colleges would be more interested in a student taking four years of language over conducting an independent, student-driven, self-directed experience. Eric notes that the prestigious Midwest college that he will attend, was thought to be out of his reach for admittance. He, however, notes the application asked for a description and an abstract, if available, of the independent work he had conducted.

With his strong quantitative-analytical interests, Eric is enrolled in AP Physics, AP Calculus AB, Independent Science study, as well as AP English, and a history elective. He is most interested in science and notes that he perceives himself as different from his classmates, who do not share this same intrinsic interest.

Eric conducted a serious organic/physical chemistry project. He made very small batches of bio-diesel using different conditions and tested his fuel to see how effective it was. He looked at a number of physical properties in the collection. Eric has conducted his project in a fume hood located in a teacher preparatory room. His teacher/mentor, a Ph.D. physical chemist, allowed him to work almost exclusively without direct supervision.

Eric was very passionate about chemistry and knew he wanted to conduct a project looking at a chemical reaction, but was not sure what reaction to examine. He had a good friend who was an avid environmentalist and they began to talk about alternative fuels, specifically bio-diesel. Eric did additional research on the chemistry of bio-diesel production and determined that it was a feasible process that would allow him to learn new techniques in analytical chemistry.

He knew, with such national political interests in alternative energy, that a bio-diesel study would be worthwhile and potentially produce novel, innovative results.

Eric's project, entitled *Cleaner air, better fuel, a solution: refined bio-diesel*, placed fourth overall in the physical sciences category at the CSF. This project was first place in environmental science subcategory and first place in the energy subcategory. He was also awarded common stock from the title sponsor of the fair, and two other special industry awards. Eric's project has reaffirmed his passion for science as he plans to major in chemistry in college. He was impressed by the powerful, positive reaction he received for his research and recognizes that it was due to the relevance of the topic on a national scale.

### *Felipe*

Felipe is a 17-year-old junior, attending a public regional high school in a middle class rural town. The town hosts the state's largest public university and the school is located adjacent to the university campus. Many students at the high school, like Felipe, have parents who are professors.

His school does not have a formal research program, but has a culture for students conducting research across diverse fields of study, many of whom work at the University. This is not the case for Felipe; he has conducted all of his research at the high school under the mentorship of his teacher. His teacher was recently awarded a prestigious science education grant and converted the school's petite, ground-level, attached greenhouse into an aquaculture center, specifically for propagating corals. Felipe has aquaria in his home and, based on his positive experience with the coral, has converted all of his tanks to salt water.

As a junior, Felipe is registered in college calculus, college physics, Latin IV, world civilizations, English, and independent study. Felipe has a strong interest in marine ecology and

the accompanying outdoor sports: kayaking, snorkeling, and scuba diving. He believes the idea of developing better propagation strategies in aquaculture is important because it will give hobby aquarists a better source of corals for their tanks, without disrupting the fragile, natural coral reef environments. After developing a functional coral system by plumbing the flow system, Felipe carefully crafted environmental studies to optimize the growth rates of a certain species of coral.

Felipe presented the results of his research entitled *Effects of lighting intensity on aquacultured zoanthid colonies*, at both the CSF and CT-JSHS. In the CSF's biological sciences category, Felipe placed fifth overall. He was also a finalist in the environmental sciences category and won four special awards.

Felipe's father is a professor of ecology and evolutionary biology at the university. Ironically, Felipe only utilized his father to dissect his paper and listen to his lecture. The experimentation, and project development was fully under the guidance of his teacher. Felipe describes his project as an offshoot of his interests in developing the aquaculture system with his teacher. He developed significant expertise during the design and construction phase and would have been satisfied just working on the system. He did, however, take the advice of his teachers to develop and present a project based on his work. He plans on continuing his work into his senior year.

### *Gabrielle*

Gabrielle is a 16-year-old junior, attending a public high school in a diverse coastal Connecticut city. Although the school has a diverse population both ethnically and socio-economically, there is a significant professional population. With a 30-mile proximity to New York City, students, like Gabrielle, have opportunities to access academic institutes and professors who often aid in the success of their projects. This is Gabrielle's second year

participating in the school's formal science research program. The school has a long, rich history with its program, being the first research class offered in a high school in the state during the academic day.

Gabrielle's project was a method development. She was seeking a strategy to grow worms in the lab, but in natural conditions. She tested different environmental and nutrient conditions extensively to see what would allow the best survival rate for the worms. Gabrielle's project origin was rooted in her strong interest in the environment. She did some preliminary work using earthworms and soil.

Her teacher recognized the project was more of a sophisticated technical project, and encouraged her to seek a project that would involve more novel work. He provided her with an article about a different species of worm and a regulatory system within the worm. The research paper was written by one of the teacher's former research students who had become a professional scientist. After examining some viability options, Gabrielle consulted with a professor in New York City who helped her focus her ideas, loaned her some equipment, and provided regular guidance, primarily by email, but once a month, in person at his institution.

Gabrielle worked primarily in her school's science research laboratory. The lab is very atypical for a high school science classroom, holding hundreds of thousands of dollars of analytical instrumentation that has been either purchased or acquired by donation. The science research teacher is a former trainer and technical support representative for a major international company that manufactures analytical scientific instruments.

Gabrielle was a CSF fair finalist and won one special award for her project *Long-term survival of "C. elegans"-lacking CED-3 in a soil-type environment*. She also placed second at the CT-JSHS. The second place award for the CT-JSHS won her a bid to present her research at

the National JSHS. Gabrielle's mentor in New York was amazed by her dedication and commitment to her work and offered her an internship for the summer. Desiring a career in research, Gabrielle has excitedly jumped at the opportunity.

### *Hannah*

Hannah is a 17-year-old senior attending a rural regional public high school in northeastern Connecticut. Hannah completed her project under the auspices of her school's senior project program. The school requires that students complete a project in any field, in order to graduate. In addition to her senior project, Hannah was enrolled in computer science, anatomy, college multivariable calculus, AP English, AP Latin V, and world civilizations.

Hannah has a strong interest in science. Working at a middle school enrichment summer science camp at a local university, she had the opportunity to speak extensively with the program facilitator, who also happens to be the co-director of the CT-JSHS. She also met with the chair of the science department during the summer to speak about possibilities. As her ideas and interests began to focus, she spoke extensively with numerous doctors and individuals about the gastrointestinal system. She worked under the mentorship of another teacher in the school's science department who earned a Ph.D. in molecular biology. Hannah commented frequently about the positive experiences she had working with and gathering information from professionals in the field. Her father, a math teacher in the school, provided Hannah with support, but fostered her independence as a self-directed learner by allowing her to seek out her own resources.

Her project, *The effect of probiotics on gastrointestinal symptoms*, was a finalist in the biological sciences category at the CSF. Hannah's project also won a governmental special award.

## *Igor*

Igor is a 17-year-old senior attending a private academy in an affluent coastal Connecticut town. Igor's chemistry teacher is running a research program with Igor and two other classmates under the cloak of an independent study. Igor is a strong political environmentalist. He is passionate about the environmental movement and in mobilizing people by informing and educating. Aside from his independent study, Igor is enrolled in AP environmental science, AP calculus, AP French, video production, as well as history and English electives.

Igor was first excited by the prospects of learning more about renewable energy resources while taking an environmental science class during his junior year. He had previously spent a semester away from home, by choice, in a southwest experiential learning institute, where he developed his deep and meaningful appreciation for the environment. He was motivated to participate in this program by a distinguished speaker who had come to his academy for a presentation. Politically savvy, Igor recognized that his passion in the environment could be tied in with a project about alternative fuels, specifically bio-diesel.

Spurred by the controversy about the minimal net energy gain from the use of ethanol, Igor developed a project to examine the lifecycle of bio-diesel, in hopes of determining that the fuel had the potential to be more energy viable. His project developed into a scaled compilation of online data. Igor was disappointed in the overall quality of his work, noting that his lack of experimentally-based data was a detriment. He gave praise to the model his friend Eric had taken for his project, who was also simultaneously working on an experimentally-driven bio-diesel project.

The two, along with a third peer, had conceived a plan where Eric would be the chemical engineer, Igor took the role of the environmentalist, and the third friend took the role of the mechanical engineer to attempt to scale up Eric's methods. Although appealing for a school-based project, when the projects needed to be targeted for the CSF judging audience, the nature of Igor's work did not optimally match the CSF format.

Igor's project, *Bio-diesel: an honest environmental assessment*, was awarded third honors in the physical sciences category of the CSF.

### *Jessica*

Jessica is a sixteen-year-old junior attending a public high school in a middle class suburban town in eastern New York, proximate to western Connecticut. Jessica has participated in her school's formal science research program all three years of her high school career. In addition to taking her school's after school research class, Jessica is enrolled in AP biology, AP calculus, AP English, AP US History, and Spanish.

Jessica has been participating in the science fair process since middle school when she studied mudslides. Each year of experience has improved the quality of her research efforts. She had read an article about mudslides and their effects on the chaparral ecosystem plant growth. She found the ecosystem fascinating and wanted to learn more about it. Her current interests are focused on chaparral plant germination cues that occur after destruction by wildfires. She found this both interesting and exciting, because there was an apparent paradox in the lifecycles of these plants: wildfires promoted their growth.

Jessica's project, entitled, *Analyzing heat shock germination cues: how environmental alterations can send a wake-up call*, placed fourth in the life science category of the CSF. She also won a special award. Her project gained admittance to the CSF fair through a regional fair

hosted in northern Fairfield County that includes neighboring New York towns. In this regional fair, she placed first in one of the life sciences category.

Jessica utilized many mentors, primarily via email. Her science research teacher, a former physical chemist researcher, assisted in the facilitation of initially contacting these individuals, as well as providing her with lab space to conduct her experiments.

### *Kyle*

Kyle is a 16-year-old junior attending a public high school in a culturally and socio-economically diverse, coastal Connecticut city, proximate to New York. Kyle has always wanted to participate in his school's formal science research program, but due to prior scheduling conflicts, he elected to take other classes, until this year. In addition to taking his school's science research seminar course, Kyle is enrolled in AP physics C, honors engineering, honors advanced multivariate calculus, AP government, honors Latin seminar, and honors British literature. A true analytical whiz, Kyle completed AP calculus his sophomore year of high school.

Kyle has always been a garage engineer, tinkering and building devices at home. He wanted to assemble a carbon dioxide laser in his basement to cut wood. This idea was vetoed by Kyle's parents. Three of his four grandparents and both of his parents are engineers. Though he has a family with a strong technical background, they allow him to be independent and self-directed in his own work. When considering what he wanted to do for his project, Kyle realized, from a practicality standpoint, that his school had a lot of optics equipment. He had a strong interest in optics and lasers and wanted to combine this interest with his desire to build something.

While rummaging through one of the storage rooms at the school, Kyle came across a sophisticated light microscope. He decided that it would be interesting to take it apart to learn more about it. During the process he thought it might be interesting to reconfigure the microscope to include a laser fluorescence system. He was unsure of what the benefit would be, but still decided to pursue it.

His teacher arranged a trip to a major cancer hospital and research center in New York City, with the goal of discussing laser-induced fluorescence microscopy. They also sought out a purpose for this sophisticated instrument he had built. Kyle ultimately decided to demonstrate the use of the microscope by measuring fluorescence *in vivo* in single-celled, chlorophyll-rich *Euglena* organisms.

Kyle's project, entitled *New techniques in fluorescent microscopy*, placed first overall in the physical sciences category at CSF. He also won two special awards. By virtue of his first place win, Kyle's project was awarded a trip to compete at the International Science and Engineering Fair (ISEF). Admittance to ISEF is only through a regional fair. Students attending ISEF have the option of competing in 1 of 17 categories (see Appendix A). Kyle chose to participate in the Physics category where he received a Third Award. CSF and ISEF participation have reaffirmed Kyle's engineering passion, as he plans to pursue it as a career.

### *Laura*

Laura is a 17-year-old junior attending a public high school in a middle class suburban town in eastern New York, proximate to western Connecticut. Laura has participated in her school's formal science research program for her three years of high school. Laura's science research class meets one night a week. Students pursue the content of their projects on their own time, often after school or during an unassigned time during the school day. In addition to taking

science research, Laura is enrolled in AP biology, honors precalculus, wind ensemble, AP English, Spanish IV, AP US history, and photography.

Laura has a passion for horses. She has been riding most of her life and works at several barns in the area. Laura also has a strong interest in learning about things that are interesting to her, although not necessarily taught in school. When Laura was a freshman, she completed a project about nutrition and degenerative bone navicular disease in horses. This work won her regional fair and earned her a bid both to CSF and ISEF. As a sophomore, she continued working on navicular disease. This topic eventually bridged into her junior-year project.

In her junior year, her equine studies became more focused. Her grandmother had read an article about reattachment surgery and was surprised to see that leeches were still used (Shin, 2006 ). This discussion with her grandmother regarding this method reinvigorated Laura and she realized that there was a potential anticoagulant medication that could be used on horses– thus the nature of her project. She developed a novel protocol to isolate and purify the anticoagulative agent from leeches.

Her project, *Integrating hirudin from “Hirudo medicinalis” into an anticoagulative medicine for “Equus caballus”*, again won the western Connecticut regional fair and a bid to ISEF. She competed in the CSF and was a finalist, winning an additional special award. At ISEF, Laura competed in the animal sciences category, earning a Fourth Award. Just as passionate about music, Laura is contemplating a double major in science and music at college.

*Summary.* Twelve students participating in the 2007 CSF participated in this study. Their projects covered a broad spectrum of topics, each suited to the individual interests of the respective student (see Table 7). The twelve students represent both urban and suburban high schools, public and private schools, as well as various socioeconomic backgrounds.

Table 7

*Summary of CSF results for subjects*

Name	Project field	Category	Placement	Subcategory	Placement	Special Awards
Andrew <sup>a</sup>	Algorithm development	Physical Science	Finalist: 5 <sup>th</sup> place	Mathematics Computer Science	1 <sup>st</sup> place 3 <sup>rd</sup> place	G (1); S (2) <sup>b</sup>
Bobby	Applied chemistry	Physical Science	Finalist: 3 <sup>rd</sup> place	Applied Technology	3 <sup>rd</sup> place	None
Caitlin	Meteorology	Physical Science	Third Honors	None	None	None
Dana	Human behavior	Biological Science	Third Honors	None	None	None
Eric	Alternative energy	Physical Science	Finalist: 4 <sup>th</sup> place	Environmental Science Energy	1 <sup>st</sup> place 1 <sup>st</sup> place	G (1); I (2)
Felipe	Marine biology	Biological Science	Finalist: 5 <sup>th</sup> place	Environmental Science	Finalist	S (2); I (2)
Gabrielle <sup>c</sup>	Cell/organism culturing	Biological Science	Finalist	none	None	S (1)
Hannah	Genetics/human systems	Biological Science	Finalist	none	None	G (1)

Table 7 (continued)

Summary of CSF results for subjects

Name	Project field	Category	Placement	Subcategory	Placement	Special Awards
Igor	Alternative energy	Physical Science	Third Honors	none	None	None
Jessica <sup>d</sup>	Ecosystem maintenance	Biological Science	Finalist: 4 <sup>th</sup> place	none	None	S (1)
Kyle <sup>e</sup>	Engineering	Physical Science	Finalist: 1 <sup>st</sup> place	none	None	I (2)
Laura <sup>e,f</sup>	Chromatography	Biological Science	Finalist	none	None	S (1)

<sup>a</sup> Pseudonym used for all subjects.

<sup>b</sup> Special awards are given from governmental agencies (G), professional societies (S), or industry (I); awards are reported by type followed by the number of awards given by that type in parenthesis

<sup>c</sup> Gabrielle placed second at the CT JSHS and presented her work at the National JSHS

<sup>d</sup> Jessica placed first in her category at a regional science fair of the CSF

<sup>e</sup> Kyle and Laura both attended the International Science and Engineering Fair and are also profiled in Table 8

<sup>f</sup> Laura placed first overall at a regional science fair of the CSF and earned her bid to ISEF through that fair

## International Science and Engineering Fair category winner student profiles

Over 1,500 students, representing over 550 regional fairs from around the world participated in the 2007 ISEF. These students, representing 46 states and 50 countries, presented their research to academic and industry professionals, as well as the general public in a gala event, taking place over the course of a week in May. The students, divided into 17 categories, based on their project content, collectively compete for over five million dollars in scholarships and prizes.

Each category awards the top projects with a first through fourth award, and a category winner. Of the category winners, three are selected as the overall fair winners and are dubbed Intel Young Scientists, receiving a \$50,000 scholarship. Of those category winners, 13 were from the United States, three were from South Africa, and one was from Hong Kong. Of the three fair winners, all were United States citizens: two were immigrants, and one was a home-schooled student. Five United States citizens, including the home-schooled fair winner, and all three South Africans participated in this study.

### *Maggie*

Maggie is a senior attending a suburban public high school near a major metropolis in a mid-Atlantic state. She has participated in her school's formal science research program for all four years of her high school career. Maggie has a spatial learning disability and has often been discouraged from taking advanced science courses.

She did not meet the eligibility requirements for admittance to AP chemistry this past year. Nonetheless, she has pursued her science research projects with fervor and has achieved great success. Maggie's science research teacher has her serving as his teaching assistant for his

freshmen classes. In addition to science research, Maggie takes calculus, AP English literature, AP US government, AP macroeconomics, and Latin.

Maggie has, as a result of her processing disability, had an interest in memory and the brain. Several years ago, she was fascinated by a PBS *Scientific American Frontiers* special that featured Alan Alda interviewing a researcher about memory in fruit flies (Chedd, 2004). She began conducting her own research about fruit flies, working with a partner. In her junior year, she and her partner won their regional fair as a team, and advanced to ISEF taking best team project in the 2006 fair. This year, her partner wanted to pursue a different course of study, but Maggie wanted to follow her interests in fruit flies and memory.

She forwarded her 2006 research paper to multiple high caliber laboratories around the US and received three offers to conduct research during the summer. She chose to work in a Midwest university laboratory and her supportive parents allowed her to move to that city for an extended summer internship. While working on her initial project, Maggie generated startling data relating to a common genetic marker, often studied during the Medelian genetics unit of a typical high school biology class. Meticulous in data collection and analysis, Maggie was constantly reviewing her data and redoing experiments to verify and validate her results. Skeptical at first, her supervisor, who gave Maggie the ability to work very independently, also recognized that Maggie's results would invalidate almost thirty years of studies conducted using this marker.

Maggie identifies this project as an accident. She was conducting other research, but the expertise she had developed over the past three years performing fruit fly studies allowed her to quickly identify the irregularity of her data and, in turn, the significance of the results she was generating.

Maggie competed in the Behavioral and Social Sciences category at ISEF with her project entitled, *Behavioral and physiological changes associated with the white gene as a phenotypic marker in w1118 and CS “Drosophila melanogaster”*. She was the category winner, thus having the top project in her category. Maggie would ideally like to pursue a career in medicine, but feels this is an unachievable goal based on her processing disability. She instead is debating between economics and her science fair interest: neuroscience and behavior.

### *Nathan*

Nathan is an 18-year-old senior attending an arts and science magnet school in the Midwest. He initially had a concentration in the arts, but transferred his concentration to the science portion of the school. As a requirement, students in the science academy must annually complete a research project. They are not under any obligation to present the results of their research outside of the school, and as a result, the projects are not always of high quality. Nathan had a desire to produce a very high quality project based on his personal hobby interests and what he considered a light senior year schedule. He was enrolled in AP biology, AP environmental science, college calculus III, government and economics, world literature, band, and tech corps.

Nathan is extremely interested in computers and computer science. For the past five years, he has regularly met with his friends for computer parties. During the parties they discuss new technology and also enjoy the latest gaming software. They also design and build new computers. A reoccurring problem that Nathan and his friends have encountered is the ability to cool processors so they operate efficiently.

Circuitry can generate a great deal of heat and it is critical to be able to dissipate the heat quickly and effectively so the computer chips do not burn out. Water cooling is the typical

strategy used for high-power processors, but Nathan felt that it was not an effective system. At one of their computer parties, one of Nathan's friends talked about a paper that was about liquid metal pumping. Nathan then spent a prolonged period at a local college library where he conducted extensive research to see if using liquid metal pumping might be an effective cooling system strategy, since it had never been attempted. After evaluating multiple liquid metal strategies, Nathan chose one that he thought would be most effective and then designed and built a closed-system circulator.

Nathan worked independently at home for the majority of his novel project. He utilized his former physics teacher as a mentor, primarily to assist him with questions about physical concepts. He was able to enlist the help of technical support experts at the industries that supplied him with his materials via telephone. In the past, Nathan had often wasted his money on materials because he did not design a good engineering plan. He wanted to avoid this pitfall with his new project.

Nathan's project, *Cooling high power density microprocessors: Employment of a liquid Gallium-Indium-Tin eutectic coolant within a magnetohydrodynamic heat transfer pump*, won his regional fair and he competed in the Engineering: bioengineering and materials category at ISEF. At ISEF, his project was awarded best in category.

### *Oliver*

Oliver is a 16-year-old senior attending a private boys preparatory school in South Africa. He comes from a fairly affluent family and speaks both Afrikaans and English at home. He lives near the coast proximate to a major city. In school he takes advanced mathematics and science classes, computer science, Latin and history.

He notes that he comes from a developing country where all students are not afforded equal opportunity, especially in education. Socially aware of his country's and continent's limited resources, Oliver comments that science classes in many high schools do not offer any hands-on opportunities because there are no materials available. Technology has only recently begun to permeate schools in South Africa, thus Oliver thought an alternative option to help with lack of laboratory resources might be to create a virtual lab system.

Unlike much educational software available, Oliver built his software system as a gaming platform. In his design, he thought it would be valuable to have a system that was modular and based on virtual reality. His experience as a computer user heavily influenced his design considerations. He also wanted educators to have the flexibility to add specific learning units with ease. Therefore, Oliver coded the system platform framework. This was the basis for the virtual reality platform.

In order to attend the ISEF in the United States, Oliver took his first international plane flight. He was amazed at the scope and magnitude of such an event, and commented about the availability of resources, especially technological ones, available to the participants.

Oliver's project, *Computer-aided instruction in the modern classroom*, competed in the Computer Science category with 64 other projects. His project was recognized as best in category.

### *Paige*

Paige is an 18-year-old senior attending a university school in South Africa. She grew up on a working livestock farm. She boards at school and returns home on the weekends. Her education path is that of a natural sciences program. She takes courses in chemistry, physics, biology, and math.

Paige was assigned an independent project as part of her school's curriculum. She had the freedom to choose her topic. So, she began a conversation with a great number of people, but ultimately deferred to her mother who suggested she do something with her farm animals. One day, she was listening to a radio program in which a farmer asked a veterinarian about the possibility of using aloe vera as a potential tick-pest control in animals. The responding veterinarian rejected the idea citing a study conducted at a university. In her usual skeptical attitude, Paige thought this might not be true, because she had heard otherwise from other farmers.

Livestock diseases caused by ticks are fairly widespread in South Africa, and there is a need for a practical, inexpensive solution to address this problem. There are current pesticide/chemical solutions available, however they are very expensive, not environmentally friendly, and the ticks typically build up immunity to the treatment usually on an annual basis.

Before pursuing aloe vera as a potential medicinal solution, Paige made extensive contacts with the local aloe factory, and interviewed the chemists as well as a large number of farmers who were interested in aloe vera as a potential treatment. Once she had collected enough information, she was able to design a study to test the effects of aloe vera on her sheep, both during the dry and rainy season. Because aloe vera has poor solubility in water, she also tested the delivery system to the sheep – both using water and paraffin as the delivery agent.

Paige won her regional fair, which is one of three in South Africa. Her success earned her a trip to the ISEF. Paige's project, *Aloe: a bitter pill for ticks to swallow*, competed in the plant sciences category. She was the category winner.

Paige received varying reactions for her project's success. Farmers were thrilled and very interested in her results, while veterinarians were quite skeptical. Paige thinks this skepticism

might be biased, since many veterinarians are funded by the chemical manufacturers. Her success at ISEF led to many newspaper articles and radio show appearances. Paige was initially not planning on attending a university, but based on her science fair success and fame, she was offered a full scholarship with a bursary to a University in South Africa. She will be the first member of her family to receive a post secondary education.

### *Quincy*

Quincy is an 18-year-old senior attending a private academy near a major city in South Africa. He lives at home with his family and is interested in pursuing a career in the sciences. He is particularly passionate about Chemistry. At school, Quincy is enrolled in all advanced courses: two math classes, science, Zulu, English, Latin and history.

Like his other South African compatriots at ISEF, Quincy is very aware and sensitive to his country's and continent's needs as a developing region. Although he does not come from an impoverished background, he recognizes the lack of resources available to his people.

Quincy has always been interested in rocketry and space. One of the problems that he has encountered while trying to pursue his rocketry interests is the availability of a suitable fuel to launch the rockets that he builds by hand. This led him to think about different possibilities for developing a working fuel formula. He found limited expertise and mentorship available in his own country and eventually made contact with a scientist in Canada, who served as his mentor. The mentor quickly pointed Quincy towards a novel strategy of utilizing epoxy for a fuel source.

After much deliberation, Quincy determined a possible, suitable formula which he synthesized and field tested, much to the chagrin of his mother, in his kitchen and on the adjacent patio. Still, his parents supported him, by funding the project and giving him space to work. He modified and adapted the formula many times to eventually generate a successful fuel mix. He

then constructed a rocket, complete with a sensor system that he designed and programmed to collect data during the launch and subsequent parachute return.

Quincy's project won his regional fair and earned a bid to the ISEF. Quincy's project, titled, *African space: fueling Africa's quest to space*, competed in the energy and transportation category. His project was dubbed category winner.

### *Ryan*

Ryan is a 17-year-old senior attending a science magnet high school in a mid-Atlantic state. Ryan is enrolled in advanced biology and mathematics, takes literature, Spanish cinema, and Russian history. His school encourages science research and apprenticeships, having in-house laboratories for electronics and stem cell research to name a few as well as providing all senior students with an internship experience. Although the school philosophy reeks of authentic experience, few students have been successful at pre-college science fairs.

Ryan, however, has been the exception. His senior-year ISEF experience is his third. Ryan's passion is electrical engineering, software-based projects, often at the sacrifice of his traditional schoolwork. His ideas are often inspired by inadequacies he observes in consumer electronics products and possibilities suggested by science fiction television dramas. His projects are often massive in scope, eclipsing even the most talented of his peers. He tends to work late into the evening or early morning.

For his senior year project, Ryan wanted to create a three-dimensional holographic generator. He had numerous ideas for completing this project, but wound up having extensive conversations with the electrical engineer-inventor to whom he was assigned for his internship. This dialogue helped him focus his design. His mentor repeatedly suggested that Ryan pare down his project: this idea was dismissed. Ryan needed to reverse engineer the projection chip

that he obtained from a used projector, design circuitry and software to run it, as well as build a mechanical table that would spin the device to generate the 3-D image.

Ryan spoke with his father to brainstorm ideas. Although his dad does not have an engineering background, Ryan feels that he is an excellent soundboard to share his ideas. His dad is good at asking questions that focus and challenge Ryan's thoughts, which, in turn, helps him to develop a solid project idea. Sometime, after conversations with his father and mentor about his big idea of a 3-D holographic generator, Ryan was travelling and stopped at a fast food restaurant, where he finally figured out how he was going to make his project work. Grabbing napkins from the metal dispenser, he quickly scribbled and scribed his design model. He noted that once he had figured out the strategy, the rest was going to be easy; it was just a matter of engineering it.

And engineer it, he did. His project, *I want a holodeck*, referencing a science fiction television series, was in the Engineering: electrical and mechanical category. The project was the overall category winner, and Ryan also received several special awards. One award of note, identified his project as one of the top three in the fair, conducted by seniors. The award is an all expense paid invitation to attend the Nobel Prize ceremony in Stockholm for the International Youth Science Seminar.

Ryan achieved significant fame during the summer after the fair for unlocking and decoding a hyped and recently released proprietary communications device. He was interviewed extensively for local and national news broadcasts. Ryan traded a second version of the device, something he considered a piece of electronics history, to the president of a communications company in exchange for an expensive sports car and a summer internship. He was

simultaneously offered summer internships and work at several major Internet search engine companies.

Although Ryan has demonstrated superior ability and creativity in electrical engineering, he feels he needs to pursue a different path for his higher education. He believes he has become a good ‘hacker’ of electronics, so now he wants to focus on ‘hacking the brain,’ thus his desire to study neuroscience.

*Scott*

Scott is a 16-year-old home-schooled junior from the Midwest. He lives on a farm. Officially, his mother is his teacher. Scott actually takes the majority of his classes at the local branch of the state university system or via distance learning with other universities. At the college, he is enrolled locally in genetics, intermediate German, world civilizations. By distance education, he is taking physics: optics and thermodynamics, AP language and composition. Under the guidance of his mother, he is independently taking differential equations and reading.

As a high school freshman, Scott was taking college chemistry at the university with college freshmen. His professor noticed that he was completing his coursework and assessments with ease and offered him an additional opportunity to conduct research in his laboratory. Scott excitedly accepted and began to complete some technical work focused around optimizing a potting soil mixture. Scott was initially excited by the experience because he was getting the opportunity to conduct authentic research, but he soon tired of it, because he ultimately found it to be lacking a challenging theoretical base without much ingenuity or creativity involved.

He met another professor whose expertise was in chemical physics. The professor was originally working on a novel polymer that could effectively clean optical surfaces. When Scott began working in the lab, the professor visited other professors abroad who were at the forefront

of nanotechnology development. They were hoping to effectively quantify the solubility of the nanoparticles they were creating. Scott and the professor headed to the main campus of the university system to use some of the advanced instrumentation and generated poor, inconclusive results.

Scott was frustrated with the data and pored over it, with no avail, for several weeks. His mentor provided him with some background literature that he thought might help try to explain the phenomena they had collected. After reading a classic paper from the 1940s, Scott realized that the strategy they were implementing was totally wrong and would never result in quantitative, conclusive results.

Based on the information, both theoretical and technical, that Scott had gathered, he devised a possible theoretical solution. Upon discussion with his mentor, the two agreed that the measurement strategy had very solid potential. Unfortunately, there was not an instrument sensitive enough to gather the data. Scott thought it might be possible to build the device. His mentor agreed and provided him with salvaged parts from throughout his department. Scott built the instrument and found that it worked beyond his expectations. This solution was truly a breakthrough in the nanotechnology field.

Scott presented his project, *Determining carbon nanotubes' thermodynamic solubility*, at the ISEF in the chemistry category. Scott was the category winner and also was recognized by many corporate and governmental groups, winning numerous special awards. Scott achieved the pinnacle of success at ISEF, having his project named one of the top three of the fair, and earning the distinguished title, Intel Young Scientist. Scott was humbled and amazed by his success, but admits it is such a pleasure to be rewarded for doing something that he absolutely loves: authentic research.

## *Tami*

Tami is a junior attending a large urban public school in a mid-Atlantic state. Tami is taking a traditional honors curriculum at school. She is enrolled in trigonometry and analytical geometry, Spanish IV, physics, chemistry, English, and AP world history. Honors science students complete research projects annually as part of their coursework.

As a freshman, Tami had a very positive experience in a semester earth science class. Having participated in the science fair process in middle school, she approached her teacher and inquired if there were any other opportunities. Recognizing Tami's talents in high school, her teacher paired Tami up with a friend at a local university. Tami was able to immerse herself into the lab's geologic study and was asked to participate in an extensive summer field excursion with a research team in Utah. Excited at the prospect of becoming a field hand and having the opportunity to learn more, Tami traveled with the team. Her job, initially, was to lug materials, help process samples, and enter data. Having gained field expertise during the excursion, Tami was allowed to work independently and started observing geological phenomena. She noticed some unique features, and with the help of the senior scientists, actually conducted a project during her field internship. This was not originally part of the plan.

Tami was able to determine a unique understanding and explanation of these geological features that had not been previously reported in the geologic literature. Returning to school her sophomore year, she prepared the data from this summer project, presented it, and, after winning her regional fair, went to the ISEF. At ISEF, she won her category and was named one of the three overall winners, the Intel Young Scientist.

Tami continued her research in Utah during the summer between her sophomore and junior year, developing a more sophisticated understanding of the features. Her project, *On shaky*

*ground: probing proximal seismites within the epicenter of a cretaceous earthquake in Grand Staircase-Escalante National Monument, Utah*, again won the regional and competed in the earth science category at ISEF. She was again the category winner and won numerous special awards for her work.

Tami continued her work the summer of her junior-senior year and plans to present these results this coming year. Tami is now regularly invited to participate in numerous professional meetings and present the results of her research. She feels her science research experience has opened the door to opportunities that she would have never conceived and looks forward to a career in the sciences.

*Summary.* Eight students participating in the 2007 ISEF plus two overlapping from CSF participated in this study. Their projects covered a broad spectrum of very sophisticated, in-depth topics, each suited to the individual interests of the respective student (see Table 8).

Table 8

*Summary of ISEF results for subjects*

Name	Regional Fair origin	Category	Placement	Special Awards
Kyle <sup>a,b</sup>	Connecticut	Physics	Third Award	None
Laura <sup>b</sup>	New York	Animal Sciences	Fourth Award	None
Maggie	Mid Atlantic	Behavioral and Social Sciences	Category winner	None
Nathan	Midwest	Engineering: materials and bioengineering	Category winner	None
Oliver	South Africa	Computer science	Category winner	None
Paige	South Africa	Plant science	Category winner	None
Quincy	South Africa	Energy and transportation	Category winner	None
Ryan	Mid-Atlantic	Engineering: electrical and mechanical	Category winner	IEEE Foundation United Technologies Corporation Seaborg SIYSS Award <sup>c</sup>

Table 8 (continued)

Summary of ISEF results for subjects

Name	Regional Fair origin	Category	Placement	Special Awards
Scott	Midwest	Chemistry	Overall fair winner <sup>d</sup>	American Chemical Society China Association for Science and Technology National Taiwan Science Education Center United Technologies Corporation Office of Naval Research United States Army Sandia National Laboratories AVS Science and Technology Society
Tami	Mid-Atlantic	Earth Science	Category winner <sup>e</sup>	Geological Society of America Society of Exploration Geophysics New Mexico Institute of Mining and Technology

<sup>a</sup>Pseudonym used

<sup>b</sup>CSF winner attending ISEF

<sup>c</sup>Seaborg Stockholm International Youth Science Seminar during the Nobel Prize Ceremony

<sup>d</sup>Overall fair winner is termed the “Intel Young Scientist” and is shared by the top three category winners

<sup>e</sup>Tami was the Overall fair winner in 2006

## Category clustering

Initial analysis of individual cases resulted in categories generated to describe salient features of concepts presented by the students. These categories are described and defined in Appendix I. A sample of categorized data from an individual student case can be found in Appendix J. As the student interview data were compiled and categorized, clusters began to emerge. Clustering of these categories is defined in Table 9. Systematic grouping based on patterns and similarities within and between categories was achieved through a collaborative discussion of peers and science students. Seven overarching axial clusters were developed to describe data across cases. They were: creative thinking, entry point characteristics, reflexive behaviors, inquiry strategies, situated learning, critical thinking, and teaching approach.

All categories are discussed either implicitly or explicitly in both the previous and following sections. The explicit discussion presented next reveals the most significant data that was derived from the study. Elaboration is provided for the categories that emerged in each cluster based on trends across multiple cases.

Most of the category clusters intersect ideas of creativity, inquiry, and situated cognition learning theory. However, some clusters (e.g., situated learning) focus more heavily on a specific concept (e.g., situated cognition learning theory). The seven categories presented here appear to be the most streamlined version of factors without losing clarity for interpretation of problem finding in open inquiry.

Table 9

*Axial clustering of categories*

Category Cluster	Categories	
Creative thinking	1. creativity	3. novel approach
	2. flexibility	4. problem finding <sup>a</sup>
Entry point characteristics	1. interests	3. previous experience
	2. interests in science	
Reflexive behaviors	1. goal	5. reward
	2. lesson learned	6. self evaluation
	3. love of learning	7. work habits
	4. motivation	
Inquiry strategies	1. background research	5. problem finding <sup>a</sup>
	2. characteristics of the scientist	6. problem solving
	3. inquiry	7. role of the scientist
	4. nature of science	8. trials

<sup>a</sup>problem finding is listed in both the creative thinking and inquiry strategies cluster because it crossed these two themes.

*Note.* Category clusters are presented in the order of presentation in the chapter. However, the categories, themselves, are listed in alphabetical order, rather than by use, relevance, or prevalence.

Table 9 (continued)

*Axial clustering of categories*

Category cluster	Categories	
Situated learning	1. application	7. new opportunity
	2. award	8. opportunity
	3. communication	9. ownership
	4. community	10. professional contact
	5. comparison	11. science fair process
	6. hot topic	12. textbook
Critical thinking	1. compartmentalization	6. project limitations
	2. conceptual understanding	7. reverse engineering
	3. critical stance	8. skeptical
	4. deep understanding	9. specialized understanding
	5. evolution of the project	
Teaching approach	1. differentiated instruction	4. role of the teacher
	2. independent	5. rules
	3. role of the parent	6. teacher interests

*Note.* Category clusters are presented in the order of presentation in this chapter. However, the categories, themselves, are listed in alphabetical order, rather than by use, relevance, or prevalence.

### *Creative thinking*

Creative thinking was a key feature for student problem finding. In fact, within the scope of this study creativity manifested itself best as problem finding. Students defined creativity as the ability and willingness to come up with a new problem or approach a preexisting problem from a new point of view. This flexible approach to questioning and posing new problems seemed to be the essence for the creative behaviors of these student-scientists. Their successes were derived from knowing that there was something new, innovative, and novel to discover, create, or build.

*Creativity and problem finding.* The majority of students (see Table 10) defined creativity in terms of problem finding. Some students also defined creativity in terms of problem solving. Only a few used more of an amorphous definition focused more generally around curiosity and “thinking outside the box.”

Table 10

#### *Definitions for creativity*

Definition	Problem finding	Problem solving	Curiosity
Number of students	13	5 <sup>a</sup>	3
Number of adults	6	1	

<sup>a</sup>one student and one mentor defined creativity in terms of both problem finding and problem solving

There was relatively little variation between the students, both from CSF and ISEF. Examples of problem finding as a definition for scientific creativity are exemplified by the following statements:

I guess creativity is, it's relevant to my science research, is finding a problem that needs to be solved. (Andrew)

I think if someone dares to raise questions about anything you want, then that person must be someone who is creative. Anything can be questioned; just not many people are willing to question everything. (Bobby)

I think creativity is being able to look at a problem and solve it in a new way. Or being able to find a new problem to solve. (Gabrielle)

I'd say that creativity is the ability to come up with different ideas and just have a different notion of things. To come up with something completely original. Something that hasn't been thought of. (Igor)

The creativity definitely comes in – choosing an idea and coming up with something original. (Laura)

Creativity is coming up with an original idea that nobody's done before. Or somebody has looked at before and you look at it at your own angle or a new angle. (Nathan)

Creativity, in the hacker sense, is taking something with a purpose and using it for something other than that purpose. That's not really a very broad definition of creativity. I don't know, maybe that is. (Ryan)

I think creativity is being able to, in one sense, take ideas that are already there and either do something new with them or improve them. Also, it's being able to look at a problem or a research, whatever you're looking at, in a way that's different from how other people are looking at it (Tami).

Adults, including mentors and a fair director, also defined creativity as problem finding:

I'd say coming up with novel ideas. Also problem solving. (Ryan's mentor)

[Creativity is] just being able to come up with ideas for things. Coming up with new ways to do things, new ways to look at things. (Caitlin's mentor)

Creative thinking is looking at a problem, that's already been looked at, from another perspective. I think that's creativity: that's a creative approach. I think creativity is thinking about a new problem. Maybe the problem is an old one, but you come up with a new technique, for example. Novelty is related to creativity: you do something new. (Gabrielle's mentor)

[Creativity would be explained] probably best as a new approach to solving a problem. You couldn't get at it the traditional way because of lack of resources, lack of ability, lack of skills. You found another way. That I think is the key to it. (Science Fair Director)

*The novel approach to a problem.* CSF documents, including abstracts and registration paperwork were examined for finalists across the fair to see if there were salient features to the types of projects that were evaluated to be in the upper quartile by the CSF judging panel. Projects fell into one of four categories: (a) literature review, (b) technical, (c) technical with value, or (d) novel approach (see Table 11).

Table 11

*Classification of projects and judging designation*

Project type	CSF non-finalist		
	Projects	CSF Finalist Projects	ISEF Projects
Literature review	2	0	0
Technical	1	0	0
Technical with value	0	3	1
Novel approach	0	6 <sup>a</sup>	9
Total	3	9	10

<sup>a</sup>the two CSF students who attended ISEF had novel approach projects. They are reported in both columns

Students who conducted a literature review project used sources for all information and organized it into a report. These projects did not analyze any data, but rather examined primary and secondary sources of research and then organized the information for a presentation.

Students completing technical projects engaged in experimental inquiry by examining a well known question with well known outcomes. These types of projects often used predetermined procedures and frequently had predictable results.

The finalists' projects fell into the last two categories: (a) technical with value, and (b) a novel approach to a problem. A project termed technical with value generally examined a phenomenon by standard methods. The student usually was seeking to measure differences in two or more groups by some specific strategy. For example, a student might have measured some environmental phenomenon like water quality and looked at multiple points along a river that might be influenced by different pollution sources. Or perhaps a student was conducting an astronomy project examining how sunspots and solar storms affected radio transmissions in a specific region. There is a level of sophistication associated with both of these examples. Both were collecting technical data which were most likely unique: the data had a unique niche that other practicing scientists might not have been directly observing and could potentially use.

These projects had a level of value because the data had the ability to contribute to the scientific knowledge base in some way. This would be significantly different from a technical project that did not contribute to new knowledge. For example, a project that measured the absorbency of paper towels or a project that tested different types of flour to see which caused muffins to rise best. Although a simple technical type of project might generate a positive learning experience for the student, it would be poorly received at a science fair, where an authentic audience of judges from academia and industry evaluate it.

A project with a novel approach to a problem was generally better received than a project with technical excellence. Students conducting a novel approach project asked a novel question or determined a novel method to solve a preexisting question. Novel approach had a level of creativity and innovation that may not have been present in a project with technical excellence. Of the projects in this study, the majority were described as novel approach to the problem.

During interviews, students easily distinguished different types of projects and identified the nature of a novel approach project. They recognized that a student who conducted a non-novel project might have had a positive experience. However, the novel project students explained that there was a level of innovation that differentiated their projects from those with technical with value. The students articulated the idea, and it was reinforced by a science fair director:

You see so many projects that say the plants will grow better in red light than they will in green light. The red light/green light project will never be a successful [science fair] project because it has been done so many times. We know the answer. You have to search for something that is not already out there. It's possible to go in depth into something that's meaningless, and that won't be a good project. It has to be innovative and novel. (Laura)

I saw a lot of projects that were interesting, but they all had to do with like measuring the water quality of a specific building. Measuring the way sewage flow worked in a specific river. And while I think that that is really interesting, those projects are all taking methodology that is out there already and reapplying it to a specific study. And they are great as studies, but in terms of experimental development, it's not like they are finding out anything that others could build on. Knowing the pollution quality of a river is important – it's a good thing to know. But it's not like measuring it is anything new.

(Gabrielle)

A science fair director, when asked to differentiate between finalist projects and truly innovative projects stated the following:

I think [the success of a project comes down to] the students' ability to sell the idea. Maybe more so than the idea itself. Although in many cases, the differentiating factor is the creativity that is apparent in looking at the work, as opposed to the work. If you had just an absolutely outstanding project that went through all of the scientific method, all of the controls, whatever it took to do the work and perfect laboratory routine. And that sort of goes against a loosely organized project, which is a brand new idea. The brand new idea is going to win (Science Fair Director).

Students who conducted novel approach-types of studies indicated that there was a level of sophistication for their projects that made them stand above a technical project:

I love coming up with the ideas. I love it on the day when I realize, “Hey I can do it like this, and I don’t think anyone’s done anything like this before.” (Ryan)

I think being novel is important, because it sticks out in people’s minds. People say, “Oh, OK, she must be doing something fantastic, if it’s on the cutting edge.” (Jessica)

The thing about my project was, I think it was sort of elegant. The way I went from a theory in a book and a theory that is used for other things like proteins and polymers and then applied this theory in a slightly different way towards nanotubes and was able to come up with my own experiment, design my own instrument. I think it was just an elegant process of going from the theory to the final conclusions and making a new discovery (Scott).

You can be a good scientist, and you can be thorough without being creative, but I don’t think you’re actually going to make anything that will change the world, or discover anything, or think of anything if you’re not going to be creative and think differently (Tami).

But creativity is what makes an engineer and scientist better than a technical person. If you can understand how stuff is working, that's half the battle. But if you can try to explore and make new things happened, that's what makes an engineer successful (Eric).

Mentors thought that the novel approach would often be challenging for students, and, at times, discouraged it. They occasionally felt that it was either too much work for the student or the student might not have the prerequisite knowledge or skill set to accomplish the task. However, those students who chose to pursue a novel approach project were successful and did meaningful, valuable research:

Coming up with a significant question I imagine would be the really most difficult part of what a kid could do. (Scott's mentor)

So she's doing something new. That almost, in itself, makes it good, I think. She's addressing a question that no one has addressed before. A lot of people try to repeat things others have done. I'm not terribly excited by doing these types of experiments. And neither is she. (Jessica's mentor)

One mentor actually described how he allowed students to go through the process of the novel approach, because of the benefit he felt it had for his students:

Many times I have to hold myself back and say, “I would do it this way.” And I try not to do that, because, (a) I don’t know if I’m always right, and (b) even if I know I am right, I know from my own experience that there is a huge advantage to figuring something out on your own, as opposed to having someone tell you how to do it. I think it is an advantage in teaching you how to think, and it’s an advantage because you’re gaining self-confidence. (Gabrielle’s mentor)

Mentors recognized they could not provide students with projects or force them to do what they, as mentors, wanted, because the student development of a novel idea would not happen:

We used to say with my Ph.D. advisor that he gave us enough rope to hang ourselves. And I really do that same thing with my students. I don’t baby sit them and tell them to do this do this do this. You really have to be an independent thinker (Scott’s mentor).

A science fair director verified that the novel approach project always had an advantage over the technical excellence project:

Answering a new question, that in real winning projects, is a question that the student comes up with. It should be a very novel question that gets researched. A mentor might inspire it. It might be the result of discussions with a mentor. It might be the student's own research into some topic that causes him or her to pose a new question that hasn't been asked before or a new way to look at an issue. That, I think, is the key to this whole thing (Science Fair Director).

Since a scheme for project classification (literature review, technical, technical with value, novel approach) appeared to emerge from the data, it was verified by a panel of practicing scientists and engineers with advanced graduate degrees (n=6). Each student project was described to the panelists and the panelists were asked to classify it into the scheme. The panelists agreed, both with the pre-established classification and each other, 88% of the time.

Documents from national and international popular press about the ISEF verify that novel approach projects are the dominant type (see Table 12). Of the 99 articles retrieved from the Lexis Nexis Database, almost everyone discussed students and their projects. Only 9 (9%) were solely about the event and 14 (14%) reported student awards. In terms of student projects, 61 (62%) referenced novel approach projects, while only 16 (16%) discussed projects of technical excellence.

Table 12

*Content of popular press articles about ISEF (2003-2006)*

Content	Number of articles	Percent of total
Novel approach projects	61	62 <sup>a</sup>
Technical with value projects	16	16
Awards to students	14	14
Event happenings <sup>a</sup>	9	9
Total	100	100

<sup>a</sup>one article discussed both awards to students and events happening. Therefore calculations of percents were based on 99 total articles where as the total column reports the number of occurrences.

<sup>b</sup>most of the event articles were about experiences for students. For example, attending a seminar with Nobel Laureate scientists, or social mixers at a science museum

In summary, creative thinking as demonstrated through a science fair project, best manifested itself as problem finding. The best types of entries were novel approach projects. Good projects often focused on observing and analyzing phenomena. However, great projects offered a novel solution to a problem.

### *Entry point characteristics*

*Students' temperament for science research.* The majority of students in this study (n=17 of 20) conducted their studies under the auspices of a formal school program. Ten of these students participated in a formal science research program or course, dedicated solely to science projects. Five completed a project as a requirement of a traditional science course in which they were enrolled. Two completed the project as part of an independent study program. Of the three who did not complete their research project in a formal school program, one (Bobby) was an exchange student attending a private school, another (Scott) was home-schooled, and the last (Quincy), attended a private school in South Africa.

Therefore, there was a high degree of self-selection for completion of a research project. All students participating in formal research classes elected to be members of their respective program. Eight of the 10 took a traditional science class in addition to their research class. The students that completed a project as part of their formal science coursework expressed a strong desire to achieve at a level higher than the expectations of the school or class:

When I got to earth science, I had really liked [the content of the class]. A science fair project is a requirement if you took an honors class. I asked my teacher if there [were] any more opportunities I could have. Or how can I go further with this. And that's how it all started up. (Tami)

One of our requirements every year is to do a project for the local science fair. So every year, a lot of people are looking for science ideas, and basically I wanted to put more effort into it. You can actually get away with it pretty easily without a lot of work, but I wanted to put more effort because I enjoyed it. (Nathan)

Ever since I was little, I've been building stuff. I love talking about the stuff I build. And now I can go somewhere and people actually want to hear about what I've built. And I've been to ISEF two times. There's a bunch of electronic projects every year from that lab to go to our regional fair. But they're usually pretty bad. (Ryan)

In addition to survey data and semi-structured interviews, the USRT Scale was used to measure students' temperament for science. Standardization of USRT scores were based on college freshmen science majors (n=274) and group score comparisons are reported in Table 13 and Figure 9. Individual scores for students participating in this study are reported in Table 14. Construct validity was achieved because the general population of science students, most of whom have not had a authentic science research experience, had a wider distribution of scores with a lower mean than the students in this study, the majority of whom completed high-quality independent projects.

Table 13

*USRT score standardization using college freshmen science majors compared with high school students participating in this study*

Descriptive factor	Standardized scores	This study
N	274.00	20.00
Mean	19.73	23.60
Median	20.00	24.00
Standard deviation	6.15	5.34
Standard error of measurement	±3.30	±3.30
Minimum	2.00	15.00
Maximum	37.00	37.00
Percentiles		
25	15.00	19.00
50	20.00	24.00
75	24.00	26.75

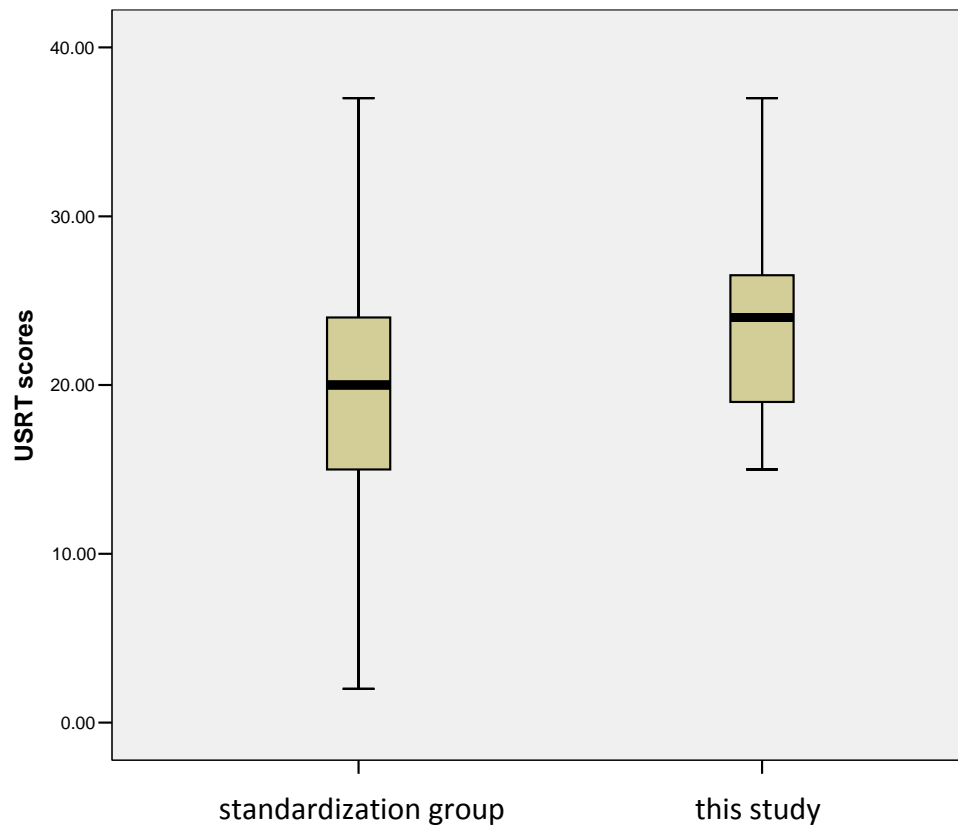


Figure 9. Boxplot distribution of USRT standardized scores compared with students in this study

Table 14

*Summary of USRT Scores for subjects*

Subject	Total Score	NCE% <sup>a</sup>
Andrew	17 ± 3.30 <sup>b</sup>	40.6
Bobby	19	50.9
Caitlin	18	44.0
Dana	19	47.5
Eric	23	61.3
Felipe	29	81.9
Gabrielle	21	54.4
Hannah	25	68.1
Igor	22	57.8
Jessica	29	81.9
Kyle	26	71.5
Laura	27	75.0

<sup>a</sup>NCE% (Normal curve equivalent) scores based on instrument standardization using freshmen college science majors (n=274).

<sup>b</sup>All scores are subject to a standard error of measurement of ± 3.3

Table 14 (*continued*)

*Summary of USRT Scores for subjects*

Subject	Total Score	NCE% <sup>a</sup>
Maggie	17 <sup>b</sup>	40.6
Nathan	26	71.5
Oliver	22	75.0
Paige	26	40.6
Quincy	26	71.5
Ryan	37	99.0
Scott	28	78.4
Tami	15	33.7

<sup>a</sup>NCE% (Normal curve equivalent) scores based on instrument standardization using freshmen college science majors (n=274).

<sup>b</sup>All scores are subject to a standard error of measurement of  $\pm 3.3$

When compared to the instrument's standardized mean average, 15 of the 20 subjects (75%) scored higher. Of the 15, 10 were in the top quartile (50% of the total sample), and 1 was above the 99<sup>th</sup> percentile. There did not appear to be a difference between top CSF students and ISEF students in their temperament for science research. The majority of the students had an affirmative indication to their positive temperament for science research, both by the USRT and through their interview comments.

*Previous experience.* Research in science is often very specialized. Professionals have very distinctive areas that they study, even within fields. Rarely would a scientist classify him or herself as a biologist, or even a geneticist. Rather terms like bacterial geneticist, or *Drosophila* geneticist, or proteomics specialist would be more commonly used. Thus, there is a distinct characteristic and description of these researchers: their area of expertise is narrow and focused. In order for some students to conduct sophisticated projects, they, too, needed to develop specialized expertise.

Often this expertise came through some experiential situation that occurred before the problem finding experience even began. Some students engaged in cognitive apprenticeships, working in an internship-like position to gain knowledge, skills, and dispositions to research in a specific field. This experience gave them the background knowledge and understanding to ask questions that others without the expertise would not have even conceived. In essence, they learned things they never knew they never knew.

Some of these students, through their research experience progression, became successful in a situated setting by advancing from neophytes or novices to having some level of expertise. This process became critical to their success because they developed the necessary capabilities to conduct a sophisticated project. The process may have taken place in a formal research setting, may have developed from years of experience conducting research, or may be a facet of practical life experiences:

And that's really where, I mean, since my freshman year project, I've made incredible leaps forward. This project would still take me a while to do, but my freshman year project I could actually do now in a day, because there wasn't much to it. So I just think it's that and so much more complicated. I can see as I've been getting older how I can look at something and how much clearer it is to me than it used to be. (Ryan)

Ninth grade, I did a project that studied the effects of albino fruit flies and immune responses and wound healing, which was basically a disaster. But it taught me the basics. It was the first time that I worked with *Drosophila*, and I've worked with them ever since. It was a good "crash course" in research. (Maggie)

So I think, just doing things throughout my life, building things in construction and making things, just doing projects at home and building things has helped me be careful and taught me how to precisely do these things in the lab. (Scott)

What I found is that doing [a project] in my junior year is actually beneficial because I was very directed more so than I would have been if I hadn't had the knowledge I had learned in the two years of science that preceded it. (Kyle)

And the longer you do projects, the more experience you get. I guess time is what I would say, mostly, and trial-and-error and things that you learn from that. Learning from your mistakes really benefits. And really having the luxury of background knowledge and luxury of knowing what will and won't work is what makes the difference. (Gabrielle)

I've built computers a lot. I'm building another one and I guess I just spent a lot of time around cooling systems naturally. Really, in the past, I previously looked at circulating mercury. That really was the precursor to this project. About a year ago, I was using a propane torch and heated up glass tubing, and started making another type of pump. I tried to get mercury. That didn't turn out so well. (Nathan)

We cleaned the Hope diamond with this polymer. We cleaned the Keck telescope in Hawaii, the biggest telescope in the world, with this polymer. The Hubble telescope. It cleans surfaces so well, better than any other processes. So I was excited to work on that project too, because I felt like, wow, I can actually be improving this product that's just an amazing, amazing polymer. (Scott)

I spent a semester out in Colorado working at the High Mountain Institute. And I got really interested in environmental studies and environmental science and when I came back home, I really got into it. (Igor)

### *Reflexive behaviors*

*Motivation.* Many students described their motivation for conducting a project describing their passion for scientific inquiry and their love of learning. Their descriptions often focused on descriptive characteristics of the creative scientist and their perception of the rewarding experiences associated with it:

The things that I knew, and the predispositions that I had, the foreknowledge that I had, was what led me to do what I did. (Kyle)

Students associated this motivation with their internal drive and sense of wonder and curiosity:

I have an extreme amount of curiosity. If I'm interested in something, I want to find out everything about it. I've always been a good student. I think of myself as an intelligent student, but research is different. (Jessica)

I think you always need to be curious and you should never, never be afraid to raise new points or do something that people haven't done before. So I should always be brave to raise new questions, be brave to think, and be a creative person. (Bobby)

Students also appreciated the opportunity to conduct a project that did not necessarily mirror the type of learning that occurs in a standard classroom. They described the opportunity as more exciting because they were participating in a different type of inquiry: one that allowed them to be independent, self-reliant, and creative. Their projects had legitimate real-world application, with a legitimate audience, not just a classroom teacher:

It was pretty intellectual, but I think actually working with my hands in the lab, building the instrument, and taking the data. You have to be creative. You have to have a very intuitive feel for whatever topic you're studying. (Scott)

It's not something – it's not an SAT-type of intellect that it takes to do research. It's a different kind of sense. (Maggie)

You need to be passionate about it. You need to have the right attitude for it. You need to commit yourself to it. That, combination along with having a really great project idea, will really make you successful. (Jessica)

The students also described the importance of valuing their work for its own worth, not necessarily to win an award:

You mustn't do a project because you think you can win [a science fair] or you think it's going to work. You must really do a project that's in your interest and that you are really passionate about. Because it takes a lot of hard work. (Paige)

I got \$50 from the Army, a bond or something at the special awards [ceremony of the CSF]. I felt proud of my project even before that. I had learned a lot. Some of the stuff was really complicated. I was proud that I had my own ideas and was able to choose this. It felt that these were skills I could apply later. (Hannah)

Mentors also desired to work with students that were self-motivated, self-directed learners. Their role, as a facilitator of student research, was enjoyable because of the independence and the ability to evaluate and adjust displayed by the students:

I want to be able to will work with the student who has some kind of directive within themselves. It comes from some internalization on their own. This is important to them, and I suspect that's what the biodiesel is to [Eric]. (Eric's mentor)

Whenever he doesn't know something, he will go away and then find the information on his own, and has the ability to self-learn. Basically, any concept he decides is important enough to know. (Kyle's mentor)

[Scott] really did the work that I would say is the equivalent to a Ph.D. student in chemistry or physics in a matter of a couple of months. I feel like it's really on a peer level that I interact with [Scott]. And I think his math is a little better than mine, actually.  
(Scott's university mentor)

*Descriptions of self.* Students were asked to describe themselves, in terms of their science project, using three different adjectives each. The question, "Name three adjectives that describe you as a person in terms of your science project," elicited responses, and were followed by elaboration of their definitions. The descriptions fell under three major categories that were in alignment with Renzulli's three-ringed conception of giftedness (1986). These categories were (a) above average ability, (b) creativity, and (c) task commitment (see Table 15).

A very small subset of the adjectives (n=3) did not meet the criteria for any of the Renzulli domains. However, these three responses all related to the applicability of the project to an audience or community outside of the traditional school setting, which is a goal of gifted behavior (Renzulli & Reis, 1986).

Table 15

*Student adjectival descriptions of themselves*

Students	Above average		Task	Applicability
	ability	Creativity	commitment	to an audience
CSF Third Honors	1	4	4	0
CSF Finalists	0	12	14	3
ISEF Category Winners	1	9	14	0
Total	2	25	32	3

The majority of the adjectives fell into the creativity (40%) and task commitment (52%) criteria. Students, almost exclusively, did not refer to their ability when describing themselves. In their creativity, they described their problem finding and problem solving. In their task commitment, they described their insatiable drive to come up with solutions:

I think the first one is creative. I think creativity for me was the paramount, because in solving any problem, a creative solution has to be reached. (Quincy)

The ingenuity is when you are faced with a problem you figure out how to get around it. I didn't work in a lab. So I [did] a lot of things due to equipment I didn't have. Things I had to get around. A large part of my project is separating out a protein. And I don't have the gels available that I could have done that with. So I used chromatography instead. It was less expensive, so it turned out to be a good thing anyway. (Laura)

I guess dedication would be one. I spent a lot of time on that. Pretty much dedication because I really never gave up on the project and eventually, it worked. There were a lot of points where I probably should have. (Nathan).

Thorough. I'm very, I don't know how to describe it, except in a condescending way, but [I'm] OCD with all of my work and everything. I write every single detail down and keep really detailed notes, so I think that that's helped a lot. Because when something doesn't look right, I'm easily able to go back and figure out. Oh, I have a decimal point 10 pages of data ago that I messed up. (Tami)

Scott discussed, not only working consistently, but maintaining that that diligence even when the challenge of a situation made it difficult. Scott noted that he needed to consider both the project challenges, but the personal ones as well:

I'd have to say perseverant. I think there were a lot of points where maybe some other people, maybe even myself, if I were in a different mindset. Maybe I would have given up or just been so stymied, that I would have just thought that, oh I don't think I'm going to get through this problem. . . And even when the problems were hard and I wasn't getting anywhere, I still came in and I still thought about it when I was sick or when I wasn't feeling well. I still worked and I still tried and I continued to proceed and make more progress (Scott).

Table 16

*Sample adjectives in each category*

Above average ability	Creativity	Task commitment	Applicability to an audience
smart, confident	novel, creative, ingenuitive, skeptical, curious, innovative, curious, adaptable, eccentric	determined, focused, persevering, lazy, responsible, studious, passionate, dedicated, intrepid	valuable, environmental, public

Mentors also tended to describe their mentees primarily with task commitment adjectives, but would more readily make reference to the students' above average ability (see Table 17). They generally described the students' work ethic when considering descriptors.

Table 17

*Mentor adjectival descriptions of students*

	Above average ability	Creativity	Task commitment
Frequency	4	3	14
Sample adjectives	Brilliant, smart, ability to learn	clever, creative, intuitive	tenacious, energetic, diligent, committed, motivated, persistent, responsible, frustrated

Kyle's mentor describes Kyle as brilliant. Even within his explanation of above average ability, creative factors emerge:

In terms of brilliant, he basically took a hunk of iron, or a microscope, that really had very little use; an older IR microscope. And he really self-educated, self taught all the concepts of fluorescence and fluorescent microscopy and took that old piece of equipment and basically built it into something that was cutting edge in terms of technology and application. (Kyle's mentor)

Ryan's mentor discussed Ryan's creativity in terms of the problem finding and problem solving encountered during his engineering feat:

Definitely creative. Creative in the sense that there were definitely obstacles to overcome. He had to figure out how to do things and he'd have the oscilloscope here and he'd be looking at the waveforms. So he'd come up with some neat investigative techniques to figure. He really reverse engineered this DLP [computer chip], because [the manufacturer] doesn't give out much information on it, because they want you to use it with their own chips. (Ryan's mentor)

Eric's mentor discussed the significant amount of time that Eric dedicated to his project:

Energetic. He was here just about every day for at least a half an hour to an hour. He's constantly looking for new kinds of things to do, more physical properties to measure, different techniques to put towards the biodiesel. Just to look to elucidate his characterization skills more. So I find that makes him very strong (Eric's mentor).

A science fair director confirmed that task commitment is a common standard feature of those conducting superlative projects:

In all cases, they are all highly committed to making it happen. They'll put in whatever hours it takes to reach their goal. There's no doubt about it. The commitment is with true zeal. You don't need someone flogging them. They're flogging themselves. They're driving themselves as hard as they possibly can to reach their goals. They're goal driven people, clearly. That's a common theme in all of our successful students. (Science Fair Director)

### *Inquiry strategies*

*The nature of scientific inquiry.* Perhaps one of the most striking similarities between and among students was their understanding of the idiosyncratic nature of conducting scientific research. The students did not feel there was a standard formula to arrive at a solution. Rather, they developed logical, analytical, and creative strategies to solve problems. The students did not choose to define their problem finding or solving as a step-by-step sequence. Their questions drove their research, not some predetermined prescriptive method of approaching scientific inquiry:

Research in itself is a different animal. You have to approach it differently. A thousand things can go wrong with it. You have to look at it from so many angles. You need to know how to look at it in the right fashion and know how to approach it. (Jessica)

A lot of people have the perception that if you're a scientist, you work very much in a linear fashion. But I've found that the greatest scientists are those who are able to think, actually. And who can draw knowledge from a number of sources. I find that when you're doing science, you have a single problem, but there may be 20 ways to approach that problem. And someone who has that liberal balance: that more creative element to him, compared to the scientist who only has that tunnel-vision and can only see things one way. (Quincy)

It's just a great feeling to have this problem that you've been working on. Stumbling with. Being frustrated with. And then finally solving it. (Scott)

I don't understand everything and I probably never will. I almost certainly never will. But everything is capable of being understood, because there are rules and laws which govern how they work. (Kyle)

I think sometimes it was frustrating because there's no right answer. No real direction you should be going in with the project. So a lot of times when I was working through my experiment and how to set it up, it would be tough, because I wouldn't have any idea if I was on the right track or not. Or if what I was doing would eventually become productive. (Gabrielle)

It's just a given, because as your experiment progresses, you're going to come to new conclusions and you're going to see new things that you wouldn't have thought you'd see. (Felipe)

*Forms of inquiry.* Through this sophisticated understanding of the nature of science, students were not bound by the confines of expectations to follow a prescriptive methodology. They were certainly not bound by a hypothesis-based testing strategy. They utilized multiple forms of inquiry to clarify their ideas and instead, they did what they thought was necessary to answer the questions that interested them:

So I think that involves a lot of quote-unquote three-dimensional thinking than regular schoolwork that we are doing at this point. Because it requires a more holistic approach to solving a problem. It's a lot more like real life, I think. (Gabrielle)

So I think I spent a long time on research and consulting before I actually began my lab work. So that might be something that happened that helped me to do better lab work, instead of doing some random work. So that makes my project as a whole: it flows very well from beginning to end. (Bobby)

I have methods, I have procedures, I have results, I have ideas of what's going on. So it was an all-you-can-eat-hands-on buffet. (Eric)

*Background research.* Pre-experimentation background research, in order to build a knowledge base, was a common, critical factor for students. Many used multiple resources: online databases, university libraries, books, and experts in the field:

There was an online tools-type thing that deals with different types of cooling technology. There was an article on pumping liquid metal. Usually they do it with liquid sodium. That's basically where the idea came from. (Nathan)

[There were] a lot of Internet searches. I didn't really get into any bookwork in the beginning. I was just mainly thinking of the project and what to decide on. There was a little bit of theory work. (Oliver)

I actually went to many department stores and malls to look at the products and buy some products that people have made. I also searched online for what ideas people have to solve this problem. So, basically, I wanted to have as broad an image as I could of what people have done. Then I could figure out a new way that no one has ever thought about. (Bobby)

So on my vacation, I went and visited the [aloe vera manufacturing] factory. I called the people before and asked if I could come and do some interviews with them. So I talked to a lot of people there. So they gave me a lot of references to farmers that have been using this. I found those farmers and talked to them. (Paige)

### *Situated learning*

*Ability to communicate well.* Students conducting research have an exceptional way of being able to communicate their needs effectively. They interact, not only with their peers and teachers, but also with professionals in academia and industry. Some build mentorship-partnerships with these adults, some only seek information to clarify their understandings or ideas. They demonstrate that there needs to be involvement with a topic or area of interest to ask a good question, to be engaged, and to learn well:

Then I asked my teacher and also some college professors. I asked their ideas – I asked if my idea is practical or if there is anything that could be improved to make the product have a better quality. It is very hard to know everything that goes on in science. So I think to talk to as much different people as you can is really helpful for a project. (Bobby)

My strength lies in being able to communicate with almost anyone in this small community. I've gotten into numerous talks with people about different alternate fuel types. I would not have been able to do this as effectively if I hadn't done a project. (Igor)

And ever since this research began, you have to talk to people. You have to be able to explain yourself no matter what you're saying. So I think a huge part of the research for life, in general, has been communication. That's definitely something that I've been able to improve upon for myself: that I don't think a lot of people have the chance to do.

(Tami)

Interaction with other people, sharing ideas with other people, that causes me to be creative. I get my ideas from them. (Andrew)

This effective communication ability transcends the problem finding stages. Students can communicate their problem solving effectively to others. The science fair director explains top students' ability to communicate at the fair:

In terms of oral communications, the ability to expand on the idea and fill in the blanks really quickly in a way that conveys the idea to you and excites you, makes a huge difference in the success of the student and the project. It's my experience, in terms of the top students that we have, one thing is for sure. If they don't go on in the sciences and engineering, they will probably go on to careers that depend on their strong communication skills, because they have them. That's almost invariant. (Science Fair Director)

*Applying knowledge.* Students recognize that the knowledge they are gaining from an open-inquiry project is often more sophisticated and specialized than a traditional academic class. The information they seek and learn transcends isolated facts of a textbook, because it is in context. The information has relevance to both them and the community of practice:

I could work a complex equation on paper or a computer program and it appeared to work, but then I had to design a system that [would] be able to be tested on the ground and actually prove and confirm the results. (Oliver)

The concept of being able to discover something and really, because I had worked in the past, and that was really dry, and textbooks. But this is really getting in there and doing something, so that is really appealing to me. (Maggie)

If you're learning in the science class, you're just learning about other people's conclusions, and other people's data, and stuff like that. So I was actually able to go and do my own stuff instead of learning about other people's. (Felipe)

[Non-research students] don't realize the other parts of [research and self reward and] they don't fully realize their capacity until they conduct a science project. So they learn a concept in physics, but they will think, "This is not really useful. How am I going to use this?" And I've learned the same concept in physics and I've used it and gone and applied it in building a rocket. (Quincy)

*Application of the research and relevance to the greater community.* As students designed and executed their research, they recognized that it should have value beyond the classroom, teacher, or school walls. In other words, their projects had authentic audiences: real people or organizations that would value the information that was generated from the project. This community was defined in different ways by the students, depending on who would benefit from the research: a local environmental organization, the medical field, the computer gaming industry, the space administration, or genetics researchers, to name a few:

[My study of the chapparell ecosystem is] very interesting, and also it relates to environmental issues, which a lot of people are very interested in nowadays. (Jessica)

[My method to effectively isolate the anticoagulant for the treatment of horses is] also something that's practical. I can see me using it. Even personally, the people that I know who horseback ride with me. It's something that could actually be used. It's actually needed for horses. (Laura)

And [a local farmer] started using aloes, and since then, he hasn't lost one cow since then. He hasn't used any chemicals, just aloe. His farm is doing very well and he's making a lot of money. It's important that my project is valuable to people in my area. (Paige)

If you can use paper repeatedly, this would avoid using too much wood or using too much energy to recycle it. That's the ideal part. I thought maybe I could make paper that I could use repeatedly, and maybe I could use water [as ink], because water is very environmentally friendly. (Bobby)

What we're trying to do is grow the corals as quick as we can under the conditions that will make them reproduce the fastest. We can take one colony and then take them out and give them to other aquarists. So less and less colonies will have to be taken from the wild and more are being aquacultured. (Felipe)

One student summarized the applicability of projects well. The project had to have an authentic audience, but may not be the be-all-end-all of research done in a field:

You need to find a question, to a certain degree, that is relevant, and something you feel can be productive. What I mean by relevant is that your research is part of the bigger picture, because even at a high school level, you're not going to be able to cure cancer. The conclusion and results from your project could at some point be applied to another field and used by some other researcher. (Gabrielle)

A mentor clarified the importance of the applicability of a student's project. He elucidated upon the idea of creativity and its relation to applicability:

The creativity in science is that you have got to take a concept and make it practical. In the process of making it practical, you can bring a relatively new concept, or a new concept that has usefulness. To bring it to the light such that it will make our lives better (Eric's mentor).

*Critical thinking.*

*Specialized understanding.* When students developed problems using a creative, innovative approach to inquiry incorporating situated learning strategy, they often demonstrated a sophisticated understanding of concepts. First and foremost, they developed a complex understanding of the content related to their project. This understanding was often much more specialized than the content knowledge associated with a traditional science class but often incorporated traditional knowledge and experiences. The students explained their projects and their ideas using a refined, scientific vernacular:

The chaparral plants actually help to stabilize the environment. The unique characteristics of the chaparral are what drew me into it. Wildfires promote their growth. I thought that was so – almost like a paradox. (Jessica)

[I'm] developing a medication that can help horses with navicular disease. Because it is incurable. It's a degenerative condition. It evolved to actually becoming an anticoagulant.

(Laura)

Because last year I worked with Prozac in fruit flies. So I knew enough about serotonin in the fly to know that this wasn't a coincidence. (Maggie)

I knew the chemical nature of the oil. I knew other techniques – calorimetry, gel point – what chemically was happening, viscosity – I understand all the units. I understand the physics aspect. I also understand the chemistry aspect. (Eric)

It makes sense to work with zooanthids because they're hearty corals, and they're really popular within aquarists. So a lot of people want them. (Felipe)

However, a lot of corrosion occurs at very high temperatures. The cesium, it wasn't really viable. Liquid metal pumping has been tested before, which is where the pump came from. But that use was not really for cooling. Really, in the past, I previously looked at circulating mercury. That really was the precursor to this project. (Nathan)

In rocketry there is an ingredient which is called ammonium perchlorate, which is very difficult to find in South Africa. But I came with the idea, that OK, adding ammonium perchlorate, what other substance can I use for that? For me, it was looking for another oxidizer, but it has to be common, and it so happens that we had a lot of potassium nitrate. (Quincy)

Stuff that I've done, like reflowing a VGA chip, or like soldering surface nanocomponents by hand that are that small, or floating something that complicated in VHDL, or getting something that massive to spin stably. Just like the things leading up to making my project work were complicated in themselves. (Ryan)

*Deep understanding.* Although students had a high content-level understanding as they developed and carried out their projects, they also understood the nature of their projects viewed through different lenses. This deep understanding usually went beyond scientific knowledge. This was more of a conceptual understanding with scientific, social, political, interpersonal, theoretical, and practical realizations. These students saw the big picture, beyond the scope of the scientific aspects of the project:

Initially what made it stand out was that these seeds benefit from their ecosystem being burned down. That's the kind of cleansing process that it goes through. It can be applied environmentally. (Jessica)

No one had ever found this before, so I had to go back and look at what was happening. And from what I can figure out, it makes sense chemically, and I don't know why scientists have never picked up on this. (Maggie)

The first thing was cost. I wanted to really reduce my costs [for the fuel I developed,] having the goal of making space more accessible to a lot more countries. Particularly for their safety. Having considered cost and safety, another critical issue was environmental sensitivity. (Quincy)

My results, particularly my gel point results, [that say] that you could use biodiesel at about five degrees Fahrenheit, were hugely important to making the field have a practical use. Because, most alternative fuels aren't really practical. That's why they're not used very often. (Eric)

So I looked through textbooks, and I looked through journal articles and then I finally realized that this method, this dynamic light scattering, wasn't the correct approach. And actually it wouldn't give you any information about solubility. So that was really my start, my beginning of working on this project (Scott).

The fact that ticks can't form a resistance to this is a very, very good point. Each year, farmers have to switch to a different chemical on their farm, because ticks keep building a resistance to it. With this product, you don't have to keep changing it, because ticks can't build a resistance to it. Also, you don't use any harmful chemicals that are bad for the natural environment, so that's also a bonus (Paige).

*Reverse engineering.* Because students often lacked the worldly experience of domains of science that a formally trained scientist would, they often had to critically and creatively figure things out without personal expertise or experience. This critical process came in the form of working backwards from what is termed reverse engineering. Reverse engineering, more frequently associated, but not limited to the engineering field, is the process of discovering the functional principles and processes of a device, object, or system through analysis of its structure, function, or operation. It often involves taking something apart and analyzing its workings in detail (Rekoff, 1985). Reverse engineering, within the scope of inquiry and creativity, took the role of knowing or having information and decoding for a useful purpose within the scope of a project. Students commented on the significance of reverse engineering, sometimes using the term, and other times describing it:

I had to reverse engineer my project. For the past four years I started with my need and my knowledge base. Then trying to figure out OK if I do this with what I already know what's going to happen? No one had ever found this before, so I had to go back and look at what was happening. (Maggie)

And sometimes the amount of expertise that I had to gain before attempting the project was also quite a challenge, i.e. learning CAD software, handling composite materials, learning how to give effective presentations in order to get funding. (Quincy)

Like what I did with reverse engineering the DLP. The way that I did it. If I wanted to solder the VGA chip and do it the proper way, I would have had to have bought a \$10,000 reflow. I bought a \$50 toaster oven. I wrote some programs and made it act like a reflow. (Ryan)

I try to figure out simple ways to do complicated things. I think of taking complicated problems and breaking it down. Thinking of some sort of trick I can do to the problem to make it easier. Or just try to think of any possible combination of ideas I could put together. (Scott)

A science fair director who is a multi-patent-holding research engineer comments on reverse engineering and students:

Well that's how all of us learn how things work. I think it's that simple. Why do they approach things that way? That may be the only way. We look at things as black boxes. You have something you don't know what mechanism is inside the box, but you apply stimuli and look at its responses, and develop a model based on those relationships. I think that's a very common denominator in all discovery-type work. I think some of these students don't have the necessary experience, or expertise, or tools, or training, or resources to do certain things. And because they don't, they have to come up with alternative ways to do things (Science Fair Director).

*Recognizing limitations.* Students noted that there were limits to work completed by scientists engaging in research. They understood that experiments and projects only produced a limited data set, which could be used as a part to construct a larger understanding of a scientific concept. Focused questions of scientists often had limited scope, and needed to be combined with other sources of information generated by other scientists or projects to more fully develop a reasonable and critical explanation of a phenomenon:

I think that I have an ability to look at other people's results and the processes that they used and find problems or things that I just didn't like about them. And figure out a new way to do that process. Like, if there's a way to analyze a seismite that someone used, and I found things that contradict that, I think I'm creative in that way. (Tami)

Scientists are constantly debating what they find. Are we going to go against their findings and are we going to justify it, and prove their point? (Dana)

Some scientists display all the data for you, so you can look at all sides, so you can have skeptics in. And some scientists only display the data that supports their conclusion. (Filipe)

I don't view [scientific topics] as one thing anymore. I try to look for different angles, different aspects. (Igor)

Recognizing that scientists compartmentalize their work, many students also used the same approach. Because the student projects often had such large scope, it was important to be able to disaggregate portions of the project so that they could focus and complete a certain portion well. This required them to clearly define and find the problem for study:

I knew the first step would have to be isolating this protein. So that's what I did first. Then I worked on purifying it. Once that was done, that [was] the first half of the research. That's what I'm presenting now: the collection and the purification. What I will continue to do, and that's plasmid transformations to mass-produce the protein. (Laura)

And I did three little projects on the process to this project. It's not like this has been my huge project that I've been working on for the past five years. No, it's nothing like that. There are parts all along the way. (Ryan)

[I]t seemed like there were a lot of different pieces to the project. Just the coming up with the correct theory. Coming up with the instrument design. Building the instrument. Running the samples. Analyzing the data. I think it was lucky how all the pieces fit together. (Scott)

I didn't have full time commitment to develop it because I was also doing another research project. Essentially I was doing two projects at once. Developing one and doing another. (Jessica)

I wanted something that would be really hands-on but at the same time not over ambitious and not something where I'd get halfway through and realize that there was no way I could finish it . . . I think mine was on the brink of not being manageable. It was challenging, but at the same time, I could do it on my own. (Gabrielle)

Because they compartmentalized well, students recognized that there were limits to what could effectively be completed in a given time frame as they determined their project ideas:

So the hardest part for me was having all the research I have here in South Africa and trying to do something here, and working with scientists that are based in the US and not being able to meet them but, being able to share ideas. That whole technology divide of me coming from a developing country was probably the hardest part. (Quincy)

Eventually I settled on *C. elegans*, because it was something that I knew was approachable in a high school atmosphere whereas doing a cell culture really isn't something you can consider. [Cell cultures] are really complicated and hard to maintain in high school laboratories. (Gabrielle)

I am only a high school student, so some ideas I came up with actually turn out not to be practical at all. (Bobby).

Mentors often recognized potential limitations in students' ideas as they designed their projects. They cautiously offered their advice, while trying not to stymie the individuality associated with developing a unique problem for study:

He didn't have the equipment which would satisfactorily do the job. So it's maybe a little bit of a waste of time: using the machine at the school. But he had never designed a real circuit board that was fabricated on the outside . . . So I think he handled these issues. He has to overcome them very maturely. He abandoned his original circuit board and then started working on the final circuit that he came up with. (Ryan's mentor)

[He] hadn't really thought enough about the big picture of "OK, why are we are doing it?" (Kyle's teacher-mentor)

In fact, the system that she has is still not the perfect system and she's still struggling to set up the appropriate experimental system to do this. So this must be annoying I suspect, but this is the way science is. (Gabrielle's mentor).

### *Teaching approach*

*Role of parents in the problem finding process.* All students reported interaction with adults as part of the processes of problem finding and problem solving. A summary of the roles of parents can be found in Table 18. The majority of students accessed their parents in a utilitarian fashion. Parents were often involved in the mechanical processes of editing work, helping with layout of posters, or listening to talks. This role took place, generally after the

problem solving was complete and the student was preparing to report the findings of the research to the greater community:

They offered great advice and assistance in the designing and making of my poster.

(Bobby)

She drove me to the JSHS. (Gabrielle)

Mainly my mother helped me practice presenting and answering questions about my research (Scott)

Even parents who had professional expertise in scientific or engineering disciplines were generally utilized for menial tasks:

My mom helped pasting onto my poster board. (Andrew)

He looked at my paper and listened to my talk. (Felipe)

However, parents also provided support and encouragement to students. The support often was emotional and financial:

I've always built things and experiments around the house, often to the chagrin of my mother. (Kyle)

They helped me acquire some of the materials that I needed to produce my research.

(Laura)

While being very supportive, they allowed me to live by myself in [a hotel] for eight weeks over the summer so that I could complete my research, they did not directly assist me in my research. (Maggie)

They funded my research and were able to tolerate the explosions my propellant caused in the kitchen . . . . I was brought up in a home where I was encouraged to be creative in thinking. (Quincy)

Parents were rarely involved in the problem finding aspects of the study. Of the 20 students in the study, only 4 report parent interaction during the problem finding phase of the project. Three of the four shared ideas together, while the fourth actually utilized her mother's expertise:

Actually, my mom is the one who cut out the article from the paper that was about the cleansing of the forests in California with the wildfires. So she was the one who actually came to me and said, "You should look into doing this. This is really neat." So I took it and looked into it for myself. (Jessica)

She had just read [a newspaper article about leeches and surgery]. And she was so surprised by the fact that they actually put live leeches on humans. They do that still during reattachment surgeries. She said, “I guess they have some sort of blood thinner in them,” and all this other stuff. It was actually at that moment that I decided, “Oh, an anticoagulant. That is something I can use and build off of.” (Laura)

He knows what a resistor is and that’s the end of his electrical engineering knowledge. He’s good with ideas. He’s good with visualizing things. He majored in pure math in college. So he’s good with that kind of stuff. He’s not good with the technical. Actually how to build this, but he’s good with “yeah well you’re going to need something that looks sort of like this.” So we talked about it, and by the end of that day, I knew what I had to do. (Ryan)

[My mom] grew up with farming sheep. She loved working with sheep. She really was very excited about this project and she really helped me out a lot. She gave me a lot of tips about how to dose the sheep. How to count the ticks on the sheep. Where you would find the most ticks on the sheep, because she has a lot of sheep. She helped me with my information and helped me gather it. (Paige)

Table 18

*Role of parents in students' projects*

Subject	Project area	Role of parents	Science expertise
Andrew	Algorithm development	Support, encouragement	Computer science
Bobby	Applied chemistry	Support, encouragement	None
Caitlin	Meteorology	Support, encouragement	None
Dana	Human behavior	Support, encouragement	None
Eric	Alternative energy	Support, encouragement	None
Felipe	Marine biology	Support, encouragement	Ecology
Gabrielle	Cell/organism culturing	Support, encouragement	None
Hannah	Genetics/human systems	Support, encouragement	None
Igor	Alternative energy	Support, encouragement	None
Jessica	Ecology	Support, encouragement	None
Kyle	Engineering	Support, encouragement	Engineering
Laura	Chromatography	Support, encouragement, discussion of ideas	None
Maggie	Genetics/behavior	Support, encouragement	None
Nathan	Computer science	Support, encouragement, funding	None
Oliver	Computer science	Support, encouragement	None
Paige	Animal science	Support, encouragement, ideas, assistance with research	None

Table 18 (*continued*)*Role of parents in students' projects*

Subject	Project area	Role of parents	Science expertise
Quincy	Aerospace engineering	Support, encouragement, funding	None
Ryan	Electrical engineering	Support, encouragement, discussion of ideas	Mathematics
Scott	Analytical chemistry	Support, encouragement, teacher, provide opportunity at university	None
Tami	Geology	Support, encouragement, funding	None

*Role of teachers and mentors in the problem finding process.* Teachers and mentors were utilized in the problem finding process. Their roles are summarized in Table 19. For some students in this study, the science teacher was the mentor. Some students used the science teacher from a traditional class, while others worked under the auspices of a formal science research program. Others worked with mentors in higher education or industry.

No participants in this study received their project idea directly from a teacher or mentor. They all developed their own ideas, based on their interests. Students often elicited conversations with these adults which helped them to focus their ideas into a problem that the student was capable of solving within the framework of limited expertise and resources:

And my mentor really helped me elaborate and focus on a certain topic and aspect of it . . . . Just talking to him and getting in touch with other people through him. It's educational, because you learn things that you wouldn't have thought about. Also, it's helpful because you can bounce ideas off of them and you get positive and negative feedback from them. It's very helpful. (Jessica)

It was really an independent thought process, but I really couldn't have done anything without the teacher of my science research class. Because a kid can do anything from an experiment in a wind tunnel to learning and memory to engineering. And he'll become an expert in what you want to talk about, so you're able to bounce ideas off of him . . . I couldn't have done anything without being able to talk to him along the way. No matter what you have to say to him, it's always a learning experience. (Maggie)

So my science teacher played a big role. He was very understanding. He took some time out of school to help me out: finding supplies, buying chemicals. So helped me a lot, and he helped me with my theory as well. (Quincy)

My mentor, the guy at the company. We usually just end up talking. We talk about random stuff. We talk about everything. Usually we talk about my project a lot. And we talk about, “Oh, you don’t have to make that that complicated. You can just do this.” Because a lot of it is refining the idea. (Ryan)

I was influenced by [my science research teachers]. Obviously, [because of their expertise] they didn’t know a lot about the field. But they would be able to tell whether or not the idea was solid and whether or not the direction I was going would be productive. [My university mentor] helped me figure out whether or not ideas were practical, because he had a lot more knowledge in the field. So what he was able to do was a question that would have taken me a few days of research and a lot of reading and a lot of fruitless online searching to solve. He would just know because he’s been working with it so long. So he helped me because I don’t have the background knowledge that a lot of people who work in this field have. (Gabrielle)

The mentors agreed with their students. They perceived their role in the problem finding experience as a support function, trying to facilitate student idea generation rather than direct students. When working with multiple students, the teacher provided the individual attention and differentiated instruction necessary for student autonomy and success. For all students, regardless of level of success at a fair, teachers and mentors were calculating in their strategy to allow students to develop their own ideas rather than present them with an avenue of study:

I tried to take her interests. I didn't try to impose what I thought would be a good project or my interests. I tried to take her interests, "What are you interested in?" And then say, "Okay see if you can find what other research is being done in this area. See if you can investigate that area." [This would help] point where those ideas might come to you.

(Caitlin's teacher-mentor)

I know from my own experience that there is a huge advantage to figuring something out on your own, as opposed to having someone tell you how to do it. I think it is an advantage in teaching you how to think. And it's an advantage because you're gaining self-confidence. It makes you feel that you know what you're doing. Which is equally important to being able to think correctly. (Gabrielle's mentor)

I don't want to say I mentored him. Ultimately, I was just somebody he bounced ideas off of. To me, that's not a full-fledged mentor. Maybe it is. He is very self driven, very independent. That is one of his strengths. (Kyle's teacher-mentor)

I'd say my role was more of a guidance role. Because sometimes we would sit here for a few hours and not working on it, but just throwing ideas back and forth. Just from my experience, I was trying to tell him things to look out for. Like things where I thought he was going down a dead end. Sometimes, he would give me a call on the weekends on my cell phone. He said, "Oh, you know, this one thing is not working right." And we would discuss ideas. (Ryan's mentor).

We discussed a lot of the theory behind that. I would show him some things – some fundamental derivations. He would finish them halfway through. I was really a guiding mentor and we would discuss things and discuss feasibility and things. Occasionally I would pull him back to reality and say, "Why don't we just do this?" or, "Let's go a little slower and make sure we understand this part and then we'll do the next part." I think that was really my role (Scott's mentor).

Perhaps Eric's teacher-mentor summarizes the role best:

So I just became his manager . . . if you will. (Eric's teacher-mentor)

Ryan's mentor eloquently summarizes his job:

So I try to foster their creativity too. Not just pushing them into one solution. (Ryan's mentor)

Mentors were often aware of potential pitfalls students would encounter with the choices they were making, but often deferred their expertise in order to have the student have a learning experience:

I didn't want to see him get caught up in all these new complexities. Sort of like going off on a tangent. I was thinking he would get so bogged down in all the complexities of interfacing directly to that chip, but he really accomplished a lot and really expanded the learning experience. (Ryan's mentor)

My impression was that he just started tinkering. Yet, my biggest concern for him was could I help him create a project that would really make use of [Kyle], and really challenge [Kyle]. (Kyle's teacher)

From an instructional standpoint, part of the challenge for a teacher acting as the mentor for multiple students in a formal program, is their lack of expertise for the wide variety of projects that students wanted to conduct. Therefore the teacher needed to maintain the role of the facilitator rather than the dispensary of information:

Part of the difficulty for me this year, was coming from a chemistry and an analytical background, and inheriting 20 to 25 kids who are all doing different things. I think part of the creativity for that type of teacher, is to be able to know just enough about what they're going to do to be able to give them guidance, and say "This is a good idea. That's a bad idea." (Kyle's teacher)

So, I think the lack of expertise was really what kind of forced them to find their own ideas. All I could do was refer them to resources that would hopefully help them. I didn't try to impose what I thought would be a good project or my interests. (Caitlin's teacher)

Table 19

*Role of teachers and mentors in students' projects*

Subject	Project field	Role of teacher	Area of expertise	Role of mentor	Area of expertise
Andrew	Algorithm development	Program administrator	Neurobiology	n/a <sup>a</sup>	n/a
Bobby	Applied chemistry	Assisted in science fair process	Chemistry	n/a	n/a
Caitlin	Meteorology	Program administrator, mentor <sup>b</sup>	Medical technology	n/a	n/a
Dana	Human behavior	Program administrator, mentor <sup>b</sup>	Medical technology	n/a	n/a
Eric	Alternative energy	Program administrator, mentor <sup>b</sup>	Physical chemistry	n/a	n/a
Felipe	Marine biology	Mentor	Marine biology	n/a	n/a
Gabrielle	Cell/organism culturing	Program administrator, mentor <sup>b</sup>	Analytical chemistry	Advice, loan of equipment, utilization of lab resources <sup>b</sup>	Cell biology

Table 19 (continued)

*Role of teachers and mentors in students' projects*

Subject	Project field	Role of teacher	Area of expertise	Role of mentor	Area of expertise
Hannah	Genetics/human systems	Mentor	Genetics	n/a <sup>a</sup>	n/a
Igor	Alternative energy	Mentor <sup>b</sup>	Analytical chemistry	n/a	n/a
Jessica	Ecology	Program administrator, mentor	Physical chemistry	Discuss ideas and results via email	Ecology
Kyle	Engineering	Program administrator, mentor <sup>b</sup>	Analytical chemistry	n/a	n/a
Laura	Chromatography	Program administrator, mentor	Physical chemistry	n/a	n/a
Maggie	Genetics/behavior	Program administrator, mentor	Chemistry	Discuss ideas, utilization of facility	Genetics
Nathan	Computer science	Program administrator	Engineering	n/a	n/a

Table 19 (continued)

*Role of teachers and mentors in students' projects*

Subject	Project field	Role of teacher	Area of expertise	Role of mentor	Area of expertise
Oliver	Computer science	Mentor	Physics	n/a <sup>a</sup>	n/a
Paige	Animal science	Assigned independent research project to class	Biology	n/a	n/a
Quincy	Aerospace engineering	Technical support	Physics	Discuss ideas and results via email	Rocketry
Ryan	Electrical engineering	Program administrator	Physics	Discuss ideas, utilization of facility <sup>b</sup>	Electrical engineering
Scott	Analytical chemistry	n/a	n/a	Discuss ideas, present a problem, provide resources, utilization of facility, externship opportunity <sup>b</sup>	Chemical physics

Table 19 (continued)

*Role of teachers and mentors in students' projects*

Subject	Project field	Role of teacher	Area of expertise	Role of mentor	Area of expertise
Tami	Geology	Mentor matching	Chemistry	Provide internship, participate in field studies utilization of facility	Geology

<sup>a</sup>not applicable

<sup>b</sup>teacher or mentor was a subject in this study

## Summary

Data collected from multiple sources (students, teachers, mentors, fair directors, documents) and methods (interviews, document analysis, surveys) were categorized to delineate salient features of the problem finding phenomenon in an extended open inquiry setting. Based on the categorization of data, seven axial category clusters emerged from the data.

The first category cluster, creative thinking indicated that student and adult scientists tend to define creative activity in science as problem finding. In addition, there appears to be a dichotomy of the types of projects that top students complete: novel approach and technical with value. Novel approach projects are generally better received and honored when evaluated by practicing scientists and engineers that served as judges at science fairs.

The second category cluster was entry point characteristics. Students who completed projects had a positive temperament for science. Also, students who completed high level projects tended to have had previous research training experiences before finding their problems for their projects.

Reflexive behaviors titled the third cluster. Students tended to have very high motivation, regardless of the outcome of their projects, they were self-regulating, and tended to describe themselves in terms of creativity and task commitment. Mentors more often commented on these students' above average ability.

When describing their inquiry strategies, the fourth cluster, students described an idiosyncratic nature to scientific investigations. All students conducted extensive background research to build their specialized scientific knowledge base.

The fifth cluster was situated learning. The data from this cluster indicated that students have the ability to communicate well with other students and adults regarding their projects.

Their specialized knowledge and deep understanding (sixth “critical thinking” cluster) developed from a prolonged situated experience. In addition, their problems had applicability to a greater community outside the confines of the school environment.

Finally, the seventh cluster, teaching approach, indicated roles of adults in the problem finding process. Parents were generally non-to-peripheral participants in the problem finding process. Teachers and mentors acted more as facilitators than knowledge disseminators and used their expertise to help students pursue student passion, rather than the adults’ interests.