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{PREFACE}

THE SCIENTIFIC METHOD: HOW DO WE FIGURE OUT WHICH QUESTIONS TO ASK?

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IF we do our jobs well as professors here at UC Davis, we will teach our students not just what we *know* though research, but also how to *do* research. But what is the right way to do research? Take a few minutes and run an image search in Google for "Scientific Method." What you'll find is a dizzying array of flow charts, each with different colored boxes with different labels, connected by a different series of arrows. Some envision a linear progression through a series of steps from hypothesis to publication, like following the steps in a lab manual that lead to a tidy result and a lab report. Other charts depict the process as a cycle, with the conclusion of one experiment leading directly to the next round. Still others describe the process as a series of forks in the road, where if an experiment supports the hypothesis then one continues to the next step, but if not, one begins again with a new hypothesis.

Which of these formulations is correct? In my opinion, all of them and none of them are correct. All of them may encompass some key steps in the process, but none encompasses the full complexity and richness of the true scientific process. More often than not, the process is messy, with multiple refinements of the hypothesis and predictions, multiple experiments, multiple false starts and setbacks, and ultimately, answers that lead to as many questions as they address. If one were to diagram the complete set of steps involved in a major scientific discovery as a series of boxes on a flow chart, it would likely be a hideous mess. In fact, after writing the previous sentence, I opened up a new PowerPoint document and took a stab at it. As you can see from **Figure 1**, it is indeed a mess. And even this mess does not completely capture all the possible permutations of the process. The messiness of this chart reflects the fact that the world is a complicated place, that our methods of measuring phenomena are imperfect but constantly improving, and that science is a human endeavor and therefore reflects human frustrations and limitations. As Figure 1 shows, there are both "*woot!*" moments and "*crap!*" moments (Fortunately, a few woot moments can sustain us through a whole load of crap).

Most undergraduate researchers don't have the opportunity to go through each step on Figure 1, proceeding from original inspiration through a published paper. There simply isn't enough time. When one joins a lab, it takes some time to learn where the interesting questions might be found, then to find the technology, methodologies and time needed to address those questions. There's a reason that it takes 5-7 years for most students to complete their Ph.D. degrees, and even this can feel rushed. Most undergraduates take part in a subset of the components on this chart, jumping in, for example, at the "Make a Plan" stage or even the "Collect and Analyze Data" stage. But ideally, students get to experience all of the major stages in the process directly or indirectly, so that they are ready to take the reins when and if they choose a career in research.

Most graduate students working on their Ph.D.s or Master's degrees will agree that picking a question to answer is one of the most difficult and intimidating parts of the process. And since it's typically the first step, it must be tackled by researchers who are often very green. In some cases, this part of the process is done by the mentor rather than the student; in other cases the student is solely responsible for picking their project. Most cases fall somewhere in between, with the student and mentor working together to choose and refine a set of questions.

Whether chosen by the mentor or student or both, the questions must be developed by someone. So how does one develop a question? Sometimes questions are inspired by observations of nature, and other times they emerge after reading theory. Sometimes it's both, as reading theory can lead us to observe things that we would otherwise have missed. Often questions emerge from research you've already done, and often they emerge from reading the research of others or hearing talks about research at conferences or seminars or in classes. Some new questions and insights emerge when trying to figure out how best to explain concepts to students; this is one of the many ways that teaching and research are complimentary at research universities such as UC Davis. In many cases, all of these sources contribute directly or indirectly to the development of research questions.

Once a question takes hold, it is typically refined through discussions with colleagues and collaborators, mentors and mentees; we even collaborate in a way with scientists of the past, by reading their work and integrating their ideas into your own thinking. But above all, developing research questions is a creative process. It's a process where you make new connections between what is known and what is unknown. People outside science often underestimate the importance of creativity in this and every other facet of science (at a high school reunion, an old classmate once asked me what I do for a living, then clearly disappointed by my answer, said "You became a scientist? But I always thought of you as so creative.")

The research experiences of two of my former graduate students illustrate how different the process of choosing a research question can be. Dr. Teresa Iglesias happened upon the topic for her Ph.D. dissertation by chance—while sitting at her desk at home, she heard a group of Western scrub-jays calling loudly and she looked out the window to investigate. She saw that the calling jays were all hopping among branches, with obvious agitation, in the trees surrounding a dead scrub-jay on the ground. This observation prompted her to read the scientific and popular literature on the responses of animals to dead members of their own species (conspecifics). She found that this behavior had been described only anecdotally in Corvid relatives of the scrub-jays—magpies, crows and ravens—but never in scrub-jays. So Teresa developed a set of alternative hypotheses for why the jays may behave this way, then she designed a set of experiments to test predictions from these hypotheses. The "*Zoinks! Zoinks! Zoinks!*" calls Teresa heard in her yard are familiar to anyone who lives in or near Davis. But these calls were especially emphatic and Teresa was sufficiently driven by curiosity to investigate and consider what she saw, then dive into the scientific literature and design a research project.

Through her experiments, Teresa discovered that this behavior isn't just a response to novelty—jays respond only to dead conspecifics and similarly-sized dead heterospecifics regardless of whether they're familiar with the individuals (Iglesias et al., 2012). Her results suggest that the behavior is an antipredator defense, where jays are using dead conspecifics as cues of threat in the area, and are calling a mob of other jays to defend against the threat.

In contrast to Teresa's inspiration from an observation in nature, my former graduate student Dr. Jessica Yorzinski found the inspiration for her dissertation project while attending a class as an undergraduate at Cornell. Jessica heard a professor lecture about research using eye-tracking technology to learn about how visual processes mediate choices in humans. Indeed, advertisers have used this technology on humans for decades to study how advertisements influence purchasing behavior. Jessica wondered whether the eye trackers could be made small enough to be worn by free-moving birds. If so, she reasoned, we might be able to gain insights into the process of sexual selection, in which elaborate ornamental traits can evolve (typically in males) through mating preferences in the opposite sex. Specifically, Jessica wanted to investigate how female aesthetic preferences might drive the evolution of the gorgeous plumage of the peacock—which has long exemplified sexual selection run amok. Jessica was aware of long-standing questions in the field of animal behavior: why do peacocks and males in other species have multiple elaborate display traits, and how do females use these traits to choose their mates? Her insight was in recognizing the potential of eye tracking technology to answer these long-standing questions.

It took many years for Jessica to develop a peafowl eye tracker with the help of engineers, then to test and refine the technology, devise schemes for calibration and measurement of error, then train peahens to wear backpacks and headpieces, etc. In the end, she discovered that peahens look mainly at the lower portion of the peacock's display train, seeming to ignore the upper region of his train during close courtship. This led Jessica to wonder what function the upper train may serve. To answer this question, she travelled to India to study the peafowl in its native habitat. There she learned that it is almost always the upper portion of the train that is visible from a distance through thick vegetation. This suggests that the different portions of the train may have evolved to play roles at different stages of mate choice: long-distance attraction and close courtship (Yorzinski et al., In review).

Teresa and Jessica nicely illustrate two of the many different sources of inspiration for scientific inquiry. Teresa began with an observation in nature and set out to explain it. Jessica started by making a creative connection between an existing question and a new technology that might be adapted to answer that question. Jessica's observations in nature came much later in the process, when she began her experiments and ultimately went into the field to try to understand patterns revealed in her captive birds. My own career has similar examples of questions from various sources: observations from nature, adapting new technology to old questions, adapting new technology to new questions, and even having questions dropped into my lap by people offering grants in exchange for research on a particular topic (this is quite common in applied sciences, such as conservation biology, where people need to understand the impact of a potential threat on a focal species).

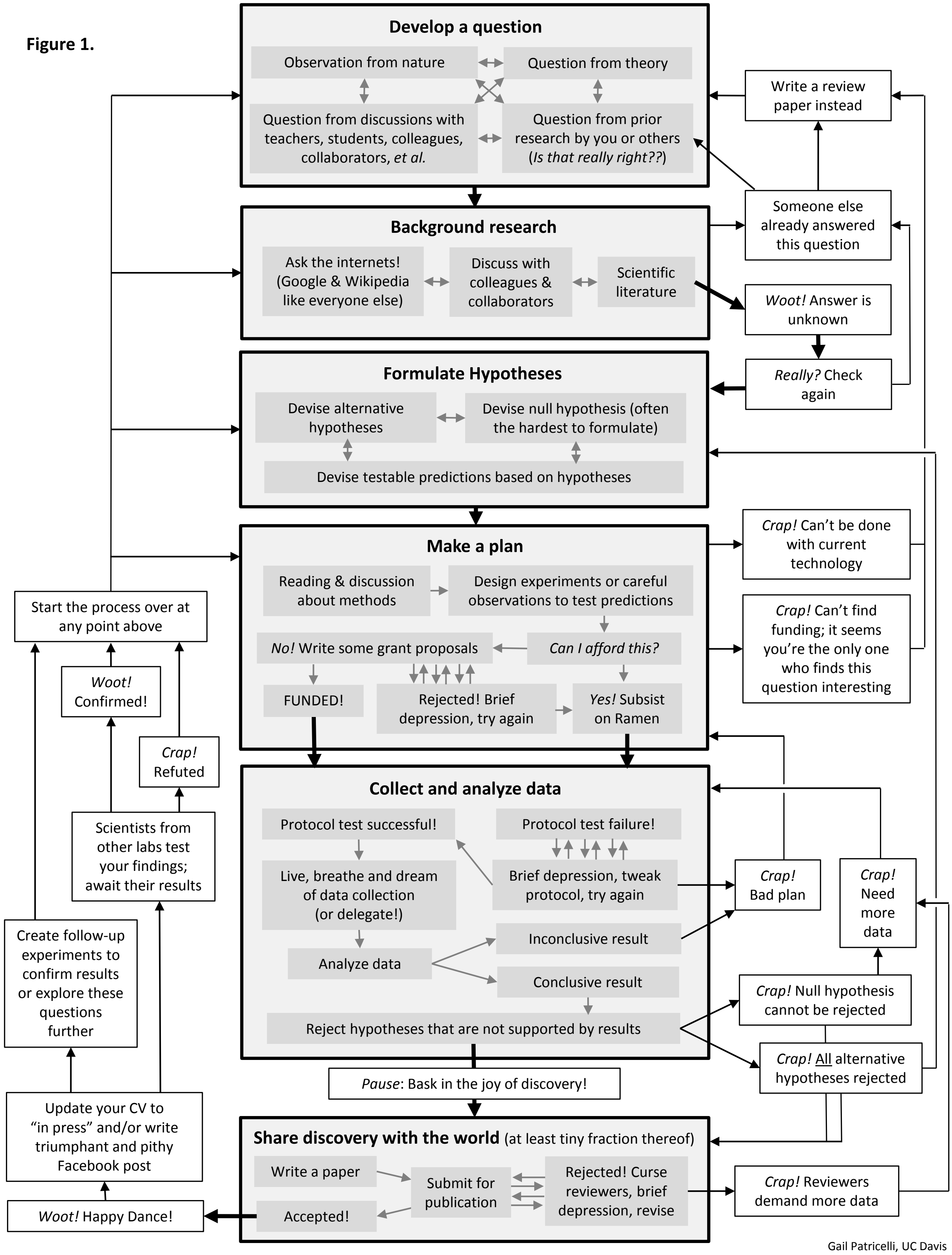
Given the diversity of methods for devising questions—and given that each step in the scientific process can also have a diversity of approaches—you can see why trying to map out the scientific process as a series of linear steps makes science seem much simpler, cleaner and ultimately less interesting than it really is. That is why most of us learn "The Scientific Method" from charts in elementary or middle school, then rarely if ever revisit those charts. Instead we learn how to do the important steps in the process: devising questions, conducting background research, formulating hypotheses and predictions, designing experimental and observational protocols, using methodological tools, running statistical tests and writing. Then we put these steps together in a new way with every project—this is where the creativity and the *art* of science come into play. This messy process ends up with a much better product than any one-way, linear process could, since it includes reaction and refinement according to the facts revealed. The process may be messy, but when doing science well, the data and conclusions are not.

Doing research well takes a great deal of practice and a lifetime of learning. The students who have contributed their work to this volume of *Explorations* the have taken advantage of the best that UC Davis has to offer—seizing the opportunity to learn the art of the scientific method, in all of its beautiful messiness.

Teresa L. Iglesias, Richard McElreath, Gail L. Patricelli. 2012. Western scrub-jay funerals: cacophonous aggregations in response to dead conspecifics. *Animal Behaviour* 84: 1103-1111

Yorzinski, Jessica L., Gail L. Patricelli, Jason S. Babcock, John M. Pearson, Michael L. Platt. Through their eyes: selective attention in peahens during courtship. In press at the *Journal of Experimental Biology*.

Figure 1.


Develop a question
Observation from nature
Question from theory
Question from discussions with teachers, students, colleagues, collaborators, *et al.*
Question from prior research by you or others (*Is that really right??*)
Write a review paper instead
Background research
Ask the internets! (Google & Wikipedia like everyone else)
Discuss with colleagues & collaborators
Scientific literature
Someone else already answered this question
Woot! Answer is unknown
Really? Check again
Formulate Hypotheses
Devise alternative hypotheses
Devise null hypothesis (often the hardest to formulate)
Devise testable predictions based on hypotheses
Make a plan
Reading & discussion about methods
Design experiments or careful observations to test predictions
No! Write some grant proposals
Can I afford this?
FUNDED!
Rejected! Brief depression, try again
Yes! Subsist on Ramen
Crap! Can't be done with current technology
Crap! Can't find funding; it seems you're the only one who finds this question interesting
Start the process over at any point above
Woot! Confirmed!
Crap! Refuted
Scientists from other labs test your findings; await their results
Create follow-up experiments to confirm results or explore these questions further
Collect and analyze data
Protocol test successful!
Protocol test failure!
Live, breathe and dream of data collection (or delegate!)
Brief depression, tweak protocol, try again
Inconclusive result
Analyze data
Conclusive result
Reject hypotheses that are not supported by results
Crap! Bad plan
Crap! Need more data
Crap! Null hypothesis cannot be rejected
Crap! All alternative hypotheses rejected
Pause: Bask in the joy of discovery!
Update your CV to "in press" and/or write triumphant and pithy Facebook post
Share discovery with the world (at least tiny fraction thereof)
Write a paper
Submit for publication
Rejected! Curse reviewers, brief depression, revise
Accepted!
Woot! Happy Dance!
Crap! Reviewers demand more data
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