This is a section of doi:10.7551/mitpress/14740.001.0001

Demystifying the Academic Research Enterprise

Becoming a Successful Scholar in a Complex and Competitive Environment

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Citation:

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DOI: 10.7551/mitpress/14740.001.0001
ISBN (electronic): 9780262377201
Publisher: The MIT Press
Published: 2023

The open access edition of this book was made possible by generous funding and support from The MIT Press Frank Urbanowski Memorial Fund

The MIT Press

4

Essential Concepts: Performing Research and Creative Activity

Chapter Overview and Learning Objectives

From the historical and scientific research methods to Indigenous knowledge and lore, research and creative activity are performed using structured frameworks and methodologies so as to ensure quality, integrity, accountability, and reproducibility. This chapter describes the concept of research paradigms and associated methodologies and the extent to which they vary among broad areas of scholarship (e.g., physical science, engineering, and the humanities) as well as individual disciplines. It also discusses how research is conducted by the general public via citizen science, the application of research concepts in daily life, and the importance of reproducibility and replicability of research results. After reading this chapter, you should

- Understand the general framework of research and be able to describe its components;
- Describe the scientific method and how it varies from the historical method;
- Explain the importance of including Indigenous knowledge and lore in research;
- Understand the differences between primary and secondary sources of information;
- Describe citizen science and its role in advancing research;
- Recognize that the process and logic underlying research methods can be applied in everyday life;
- Understand the differences among reproducibility, reliability, and replicability of results and their importance in research; and
- Recognize the roles played in research by serendipity.

4.1 General Framework

Working within a structured framework, adhering to certain principles, and following certain procedures when performing research and creative activity ensure the outcomes have several important properties. Among them, results should be of high quality; they should, when appropriate, be reproducible and replicable as well as reliable; they should reflect thoughtfulness and integrity in design and execution; they should add to and not duplicate the existing body of knowledge; and they should be worthy of the funding and resources used to support them.

Because of the wide array of disciplines in which research and creative activity take place, an equally wide array of methodologies exists. Indeed, many disciplines offer courses in research methods, and entire books (e.g., see Bulmer 2003; Crowther and Lancaster 2008; Wilson 2008; Smith 2012; Groat and Wang 2013; Christensen et al. 2014; Punch and Oancea 2014; Drawson et al. 2017; and Litosseliti 2018 in the references) are devoted to specific methods in education, business, sociology, social work, psychology, law, the arts and fine arts, humanities, science and engineering, and others. Topics covered typically include historical overviews of research in the given field, along with considerable detail regarding research approaches, the collection, analysis, and interpretation of data, hypothesis formulation, sampling, experiment design and execution, and interpretation and presentation of results.

Not surprisingly, terms describing certain aspects of research methodology in one discipline sometimes have a different meaning in other disciplines. Examples include words such as paradigm, approach, method, philosophy, and design. Consequently, given that research methods are almost a discipline in and of themselves, I do not attempt to provide any sort of summary of methods for individual fields of study. Instead, I provide first a somewhat generic overall framework for research and creative activity, borrowing from a number of disciplines and utilizing terms that have the same general meaning across them. I then examine a few specific methods to give you a flavor of their similarities and differences. As a next-generation scholar, you should become intimately familiar with research methods in your own discipline and explore methods in a few others. Doing so not only will facilitate your own work but also prepare you for multidisciplinary collaboration (chapter 13). Additionally, it will allow you to borrow concepts from other disciplines to enhance the application of methods in your own.

In general, research can be divided into three categories (figure 4.1): qualitative, quantitative, and mixed. These terms usually are described as the foundational elements of the research framework, philosophy, scheme, or paradigm.[1]

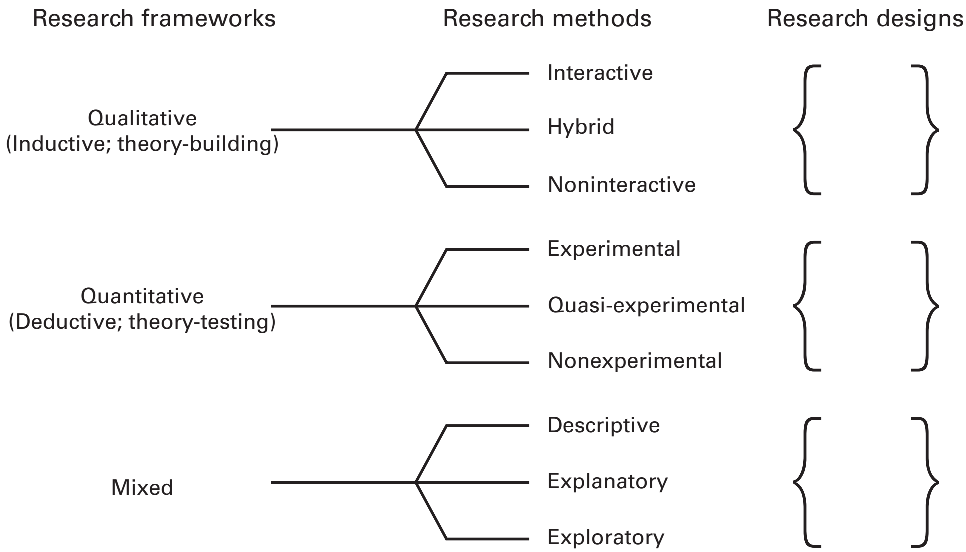

Figure 4.1
A general research framework. *Source*: Adapted from Khaldi (2017, figure 2).

Qualitative methods involve the extraction of meaning via descriptive analyses or interpretation, which makes the results more subjective but nonetheless still valuable as they are determined using a structured approach. Qualitative methods often utilize inductive reasoning, which begins not with a theory, but rather with observations. This “bottom up” approach (figure 4.2) begins with specifics, such as detailed behavior observed regarding some phenomenon or situation. It then proceeds to more general notions by identifying patterns or other structures within observations/data that explain the behavior, resulting in one or more hypotheses and eventually a theory. For this reason, qualitative methods often are referred to as theory-building methods.

Conversely, quantitative methods utilize numerics and frequently involve the use of statistics and the development of computational models. In this regard, the results tend to be objectively determined. Quantitative methods typically utilize deductive reasoning (figure 4.2), which begins with a general concept or theory and then sets out to test one or more associated hypotheses based upon observations or other data collected. This “top-down” approach therefore proceeds from the general to the specific through systematic investigation until reaching a final, specific conclusion. For this reason, quantitative methods often are referred to as “theory-testing” methods.

Another dimension of both qualitative and quantitative research methods is empiricism or the empirical approach. The word “empirical,” as applied here,

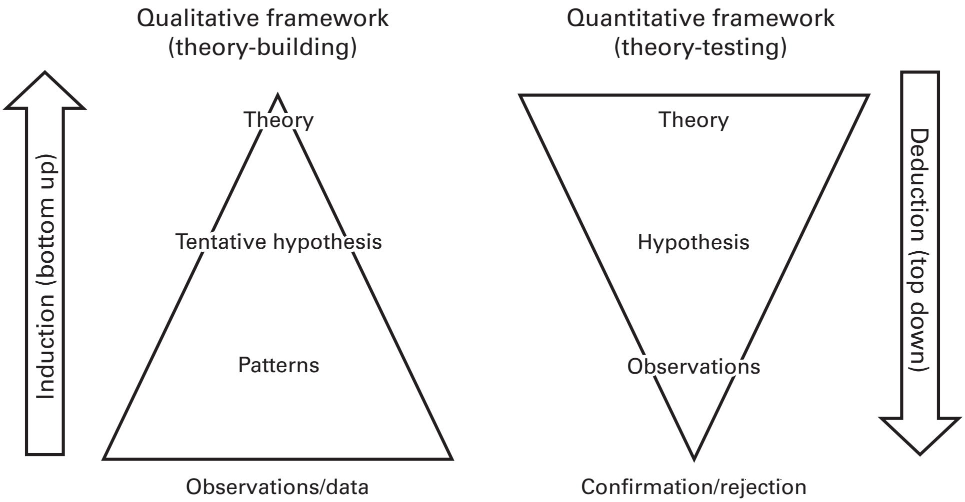

Figure 4.2
Inductive/qualitative and deductive/quantitative research frameworks. *Source*: Adapted from Khaldi (2017, figure 1); Burney and Saleem (2008); Research techniques (2015).

refers to research that can be verified by observation or experiments, as opposed to conjecture, philosophy, or logic. Empiricism involves gathering evidence to answer a question or test a hypothesis (more on hypotheses below). Applied to quantitative research, empiricism might involve collecting and objectively analyzing radar data on a wide array of thunderstorms in an effort to evaluate one or more theories regarding tornado formation. In the context of qualitative research, empiricism might involve assessing interviews from individuals regarding their opinions about a specific historical event. In both cases, the outcomes of the research can be traced directly to verifiable data or information, though using substantially different approaches.

Not surprisingly, numerous research studies do not fit neatly within either the qualitative or quantitative frameworks, giving rise to the application of mixed research methods (figure 4.1). Such hybrid approaches are extremely powerful in that they combine the attributes of both foundational frameworks and thus are particularly well suited for work involving multiple, especially disparate disciplines (chapter 13).

Within the qualitative/quantitative/mixed methods framework just described lies a great deal of complexity. As shown in figure 4.1, qualitative research can involve the application of interactive, hybrid, and noninteractive methods. In the interactive method, the researcher is directly involved with or immersed in the study, such as interviewing a focus group, whereas historians typically utilize the noninteractive method, as when relying upon source material from written documents, recordings, and images produced by individuals who may be deceased. As you will find, additional layers of complexity exist beyond these, extending into specific instruments for gathering and analyzing data, for example. They are indicated by the curly brackets in figure 4.1.

Quantitative research generally is viewed as experimental, quasi-experimental, or nonexperimental. Although these terms have substantially different meanings across disciplines, the word "experiment" generally involves a process or set of processes over which the researcher has complete control, especially in manipulating certain parameters to determine their impact on the end result. The aforementioned example involving the collection of radar observations of thunderstorms is an example of a nonexperimental approach.

All three of the foundational frameworks are used in disciplines ranging from science and engineering to arts, social sciences, and humanities. And each contains numerous possible designs and execution strategies (shown by the empty curly brackets in figure 4.1). Although quantitative research generally is viewed as necessarily reproducible (section 4.7) and yields statistical confidence in or other quantifications of the results, qualitative research generally is not—yet has the advantage of being applicable to situations that are not amenable to quantitative methods.

Finally, research within the general three-part framework can be either independent or directed. In directed research, such as that performed by college undergraduates or students pursuing master's degrees, or amateurs involved in citizen science (section 4.6), the work is overseen by a professional researcher who provides considerable input and directs the work as it proceeds. In contrast, independent research, which is performed by professionals, postdocs, and doctoral students, is for the most part not overly influenced by an advisor, though of course ultimately is judged by peers in publications, performances, exhibits, dissertations, and other forms of presentation (chapter 11).

4.2 The Scientific Method

The foremost example within the deductive/quantitative framework described previously is the scientific method. In fact, is it not a single method but rather, as shown in figure 4.3, a general set of principles, appropriate for a wide array of disciplines, within a flexible procedural structure. That is, multiple starting points exist within the structure, and the ordering of and interaction among steps can vary depending upon discipline or type of study being undertaken. Ultimately, application of this structure leads to understanding of cause-and-effect

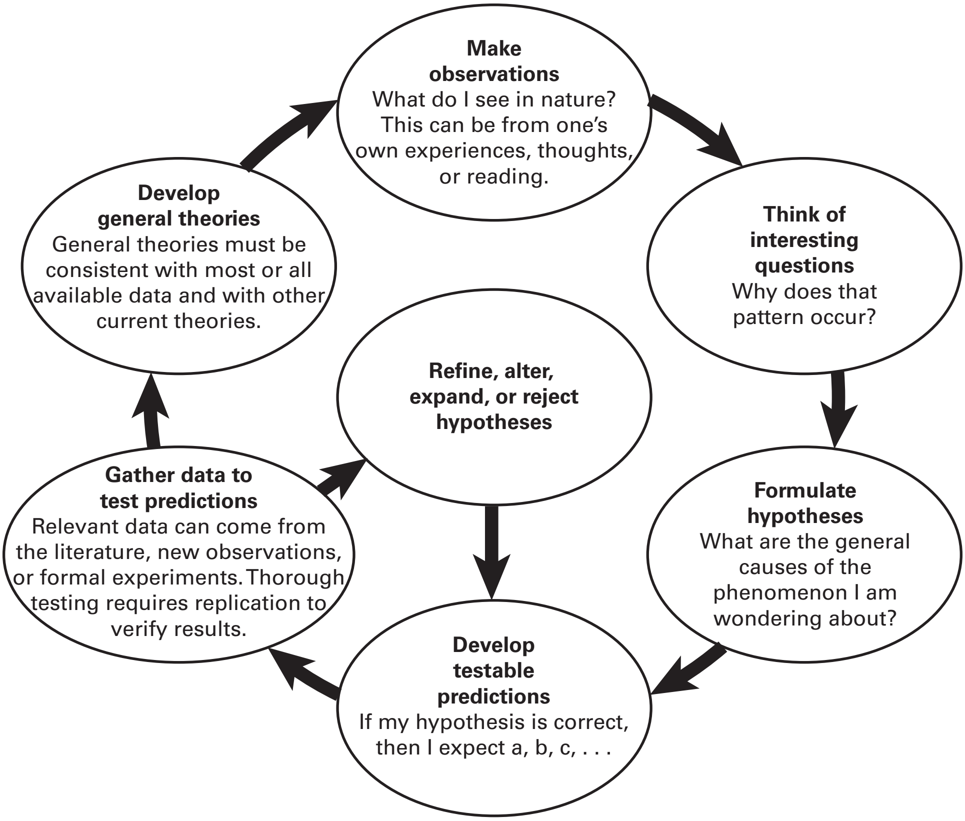

Figure 4.3
The general scientific method as an ongoing process. *Source*: Wikimedia.org. Used with permission of Creative Commons License (CC BY-SA 4.0; https://creativecommons.org/licenses/by-sa/4.0/deed.en).

relationships via experimentation, regarding questions posed by the researcher. The scientific method is based principally upon empirical or measurable evidence though can involve qualitative, nonempirical elements as well.

Application of the scientific method generally begins with a personal awareness of some facet of the world, or some professional interest in a particular phenomenon or process, which leads one to ask questions. How does the SARS 2019 coronavirus mutate? Why does a particular painting or dance evoke such strong emotion? Why did the Roman civilization not persist? Why is a particular form of cancer susceptible to therapy while one very similar is not? Consequently, the "make observations" and "think of questions" balloons in figure 4.3 can be interchanged. That is, informal observations of the world in which we live, leading to questions such as "I wonder why rivers do not flow in a straight line?" are different from observations collected formally as part of a structured research process (figure 4.2). The latter seek to answer questions posed at the outset of the study but also lead to additional questions being posed.

An important consideration in research involves determining whether the question or questions being posed already have been answered. In some cases, such as the examples just provided, the answer is obvious. Indeed, we know exactly why rivers do not flow in a straight line. For other questions, say involving a particular form of cancer, the answer may exist in the form of making incremental progress rather than arriving at a conclusive yes or no.

If the question being posed remains unanswered, or additional knowledge can be gained through further investigation, then becoming more familiar with the topic is important. That is, one needs to review the existing body of knowledge to understand what work has been performed previously and how answering new questions will advance understanding. Once that review has been conducted, the researcher characterizes the subject of inquiry by making formal measurements or observations. And as noted previously, the very process of making measurements or observations can lead to additional questions.

A critical component of the scientific method, once general questions have been formulated based upon observations or other information, involves the generation of hypotheses. A hypothesis is an informed conjecture, or educated guess, that offers a plausible explanation for the observations made or answers to the question(s) being posed. In some cases, hypotheses are formulated mathematically and tested with rigorous statistical analysis—the goal being not to *prove* the hypothesis, but rather to *accept or reject it* based upon measures of statistical significance that address whether the outcome may simply be due to chance. This approach is commonly applied in the social and behavioral sciences.

Well-formulated hypotheses lead to another important element of the scientific method, namely, predictions (figure 4.3). The prediction might involve the presumed outcome of an experiment in a laboratory setting, such as a chemical reaction, or an observation of nature, such as lightning in a thunderstorm. How does one test the prediction? Via experimentation, which is another important step in the scientific method.

It is important to recognize that hypotheses and experiments are not the domain of the sciences alone. In fact, hypotheses often are tested via experimentation in dance studios, on the stage, in art exhibitions, and in the orchestra pit. Experimental results and analyses that support predictions and observations might lead to acceptance of the hypothesis. However, sometimes experiments contain errors in formulation or execution, and observations also can contain errors. For this reason, experiments frequently need to be repeated using different sets of observations (section 4.7). Additionally, as described below, one must not modify hypotheses midstream, or tamper in dubious ways with observations, because doing so—with the purpose of obtaining desired results—would violate principles of research integrity (chapter 9).

Depending upon the outcomes of experiments, additional testing can be performed and other hypotheses evaluated. Ultimately, the work might lead to the verification of a theory, which is an explanation for some phenomenon, behavior, or observation that is still subject to uncertainty and testing. Indeed, theories are not facts or evidence, but rather explanations of them. No theory is ever considered final or complete because new evidence always arises, perhaps not overturning the theory itself but placing it in the context of other, broader theories (as is the case for the structure of the atom). Note that the word "theory," as applied in the scientific method, is quite different from that used in regular conversation. This is one reason why topics such as climate change, which is founded upon theories of how the earth behaves and how humans influence this behavior, often are misunderstood by the general public.

Another important term in scientific research is the word "law." Laws, such as the law of gravity, describe the behavior of a phenomenon in the natural world, and the law always holds true. But the law does not explain *why* the behavior occurs. Theories, on the other hand, explain observations, but can change or be refuted with time as understanding grows or additional observations and understanding become available.

4.3 The Historical Method

The historical method, which is an example of qualitative research (as noted previously, quantitative research methods also are used broadly across the humanities), consists of techniques and guidelines by which historians use primary sources of information (that is, original writings, recordings, interviews, and other materials) to develop their accounts of the past. Of course, they also rely upon other sources, as do all scholars, in building upon the current state of knowledge.

One important aspect of historical research involves the reliability of source material, which is the analog of reliability of observations in the scientific method. When and where the source was produced, by whom, its reliance upon earlier material, its original form, and the credibility of its contents all are critical elements to be considered. Collectively, these are known as *source* *criticism*. Of course, different sources often contain differing accounts (e.g., the assassination of President Kennedy) or lead to different conclusions, and thus contradiction needs to be considered. Rigorous procedures exist for addressing contradictions in sources, including factors such as degree of authority, eyewitness accounts, source independence, and extent of source disagreement. Anonymous sources require particularly careful vetting.

Once sources have been identified and fully evaluated, hypotheses then are constructed in a manner similar to that used in the scientific method. However, because *quantitative* hypothesis testing usually is not applicable to historical research, other techniques are used to arrive at the best explanation for the hypothesis given.

For example, the hypothesis must be of greater *explanatory scope* than any other incompatible hypothesis about the same subject; that is, it must imply a greater variety of observation statements. The hypothesis must be of greater *explanatory power* than any other incompatible hypothesis about the same subject; that is, it must make more probable than any other hypothesis the observation statements it implies. The hypothesis must be *more plausible* than any other incompatible hypothesis about the same subject; that is, it must be implied to some degree by a greater variety of accepted truths than any other. And so on.

Noted historian C. Behan McCullagh sums up the historical method quite nicely by saying, “if the scope and strength of an explanation are very great, so that it explains a large number and variety of facts, many more than any competing explanation, then it is likely to be true” (McCullagh 1984, 26).

4.4 Indigenous Methods

The research frameworks and methods previously discussed in this chapter were developed within the context of Western civilization. They emerged as study of the natural world became systematized (sections 3.5 and 7.1) and emphasis began to be placed on quantitative/theoretical as opposed to purely descriptive/phenomenological approaches. Consequently, a vitally important dimension of research and creative activity, *relevant to all areas of inquiry*, became increasingly sidelined—namely, the engagement of Indigenous communities.

Although the very meaning of the terms “Indigenous communities,” “Indigenous peoples,” and “Indigenous research methods” continues to be debated, one fact is not debatable. Namely, the extent to which traditions, values, perspectives, observations, and knowledge of the world—gathered over thousands of years by Indigenous communities—can enrich not only research, but also *contemporary approaches* to research. Examples of the former include but are not limited to topics such as climate change, variations in ecosystem structure and function, diseases in animals and plants and how they are influenced by the environment, art, evolution of oral and written communication, religious and cultural ceremonies, social and familial structures, community governance, and entertainment. Indeed, the use of cultural burning to manage forests is an important practice of Indigenous Americans, and the federal government now has embraced such Indigenous knowledge in managing the Western US wildfire crisis.

The worldview of Indigenous communities with regard to culture and history differs substantially from that of others, and thus adds tremendous depth to the tapestry of knowledge and approaches available for understanding our world. Nevertheless, this fact frequently is overlooked. All too often, studies are conducted *about* Indigenous communities rather than in authentic *partnership with* them. Consequently, such communities tend to be marginalized in the research process because relationships were not developed, cultural context was not understood, Western approaches to research were presented as the sine qua non, and benefits of research outcomes to participating communities were not delivered. These factors, among many, reinforce notions of colonialism and tokenism, which is especially troubling during a time when diversity, equity, inclusion, and belonging are espoused as high priorities for the academic enterprise.

Although the numerous research methods and approaches in common use today are not incompatible with Indigenous engagement, particularly those of a qualitative nature, they can, because of their Western origin and rules-based frameworks, tend to portray Indigenous populations as subjects having limited power or influence. In their review of Indigenous research methods, Drawson et al. (2017) describe it this way: "One distinction between Western and Indigenous research methods lies in this purpose: research done in collaboration with Indigenous Peoples cannot only reveal knowledge, but also decolonize, rebalance power, and provide healing."

Work by Snow et al. (2016) is useful for further understanding this important notion, and in it they identify six overarching principles for engaging researchers in "practices that privilege the voices and goals of Indigenous populations." They define such populations as "individuals or groups belonging to developing or underdeveloped regions nationally or internationally, as well as those who have been marginalized by Eurocentric values and/or research methodologies." They further note that "Indigenous research recognizes Indigenous communities develop shared ways of knowing guided by how they view the world, themselves, and the connection between the two."

The six principles from Snow et al. (2016) are as follows:

- Indigenous identity development—researchers becoming familiar with Indigenous culture and norms prior to beginning work;
- Indigenous paradigmatic lens—applying research approaches not in isolation from but rather in the context of Indigenous culture and norms;
- Reflexivity and power sharing—building positive relationships among everyone involved and ensuring that individuals other than researchers can bring ideas to the table;
- Critical immersion—complete awareness of self and others in all aspects of the research process;
- Participation and accountability—conducting research according to the highest ethical standards (chapter 9) and empowering all participants to contribute and participate in the entire research process; and
- Methodological flexibility—researchers being willing to modify traditional research processes and frameworks to accommodate Indigenous culture and norms, though always without compromising research integrity.

Even with this brief overview, it should be clear to you that Indigenous research methods implicitly include Indigenous norms, perspectives, and values. I especially like how Wulff (2010, 1290) captures this notion in his review of Indigenous research methods that is informed partly by Wilson's work. Wulff states that "Research is simply another practice or articulation of an Indigenous life, no more, no less." In her book on research methodologies, Smith (1999, 15) notes that "Indigenous methodologies tend to approach cultural protocols, values and behaviours as an integral part of the methodology."

Much insight can be gained into the world in which we live—from how the earth behaves and humans influence it to concepts of self-determination, self-governance, and family and community structure—by conducting research in collaboration with, and not simply on, Indigenous communities. An exercise at the end of this chapter challenges you to identify ways in which your own research could engage Indigenous communities.

4.5 Integrating Research and Education

As described in section 3.5, education and research are inextricably linked. Education is both a discipline within which research is performed, as well as the many-faceted process by which learning takes place as part of research itself. The former is critical for understanding how individuals and groups of individuals learn, and in developing effective methodologies for promoting such learning not only in formal education, but also over the course of one's life.

Yet, education research, like education itself, does not exist in a vacuum. Rather, it is conducted within the context of a wide array of disciplinary communities—ranging from science, engineering, and the life sciences to the humanities and arts. In this regard, education research shares a number of characteristics with Indigenous research discussed in section 4.4.

During the past few decades, a framework known as discipline-based education research (DBER) has emerged. It describes research that "investigates learning and teaching in a discipline using a range of methods with deep grounding in the discipline's priorities, worldview, knowledge, and practices" (National Research Council 2012a). In fact, DBER has fostered the creation of communities (e.g., science and education research community, faculty development research community, higher education research community), recognizing that each has its own culture, norms, practices, tools, perspectives, and indeed, research methods. Do you see the similarities to Indigenous research methods?

Interestingly, DBER is not a research method, but rather a framework of study that utilizes a wide array of methods to answer questions at the intersection of education and specific disciplines. The DBER framework for engineering is shown in figure 4.4.

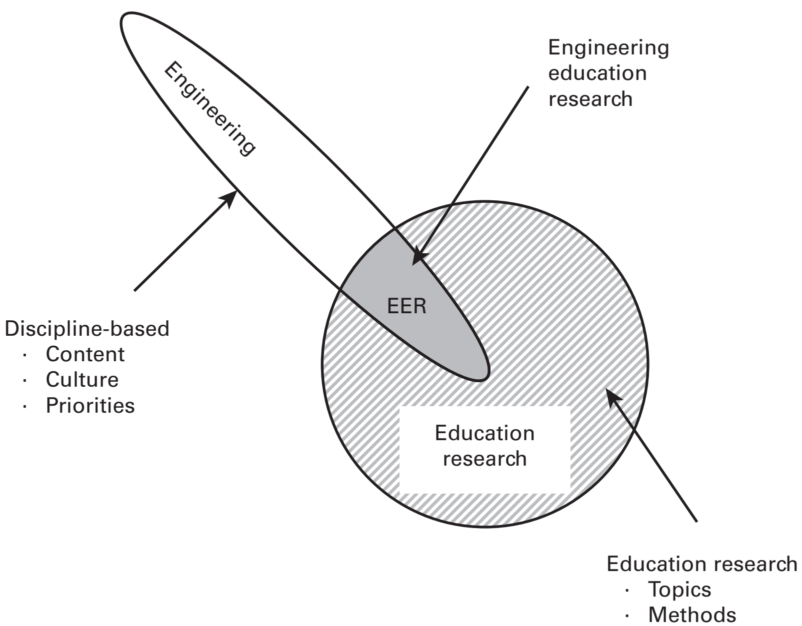

Figure 4.4
An example of DBER in engineering. *Source*: Henderson et al. (2017). Used with permission of Creative Commons License (CC BY 4.0; https://creativecommons.org/licenses/by/4.0/).

Although DBER is geared toward STEM disciplines with the goal of improving science and engineering education, the framework is applicable to all academic fields and thus can utilize all methods for research described previously in this chapter. DBER specifically embraces the flexibility of approach described in section 4.4 for Indigenous methods, and thus is a canonical example of collaborative, multidisciplinary research (chapter 13).

4.6 Broader Application of Research Methods: Citizen Science and Daily Life

Lest you believe research and creative activity are the sole domain of academic scholars, government and private sector researchers, or advanced students, think again! The general public—that is, amateurs, rather than professionals—increasingly are involved in research in what has come to be known as citizen science, crowd science, or crowd-sourced science. Although the terms are relatively new, having been coined in the mid-1990s, citizen involvement in research goes back a long way. In my own field of meteorology, the cooperative weather observer network has been around for decades. In it, volunteers are trained to make regular observations of weather at their homes, businesses, or other locations, and this information is fed into weather forecast models and also used in weather and climate research studies.

Most citizen science involves directed research (section 4.1). In this approach, volunteers engage, with appropriate oversight, in research. They apply elements of the scientific method, and they fulfill their desire of contributing to new knowledge without necessarily holding a degree or even being formally trained. Citizen science is supported in many ways, including by public and private museums, science centers, and even research universities. One of the most famous citizen science efforts is the Search for Extraterrestrial Intelligence (SETI). Now a nonprofit institute dedicated to public education and the advancement of science, SETI is perhaps best known for its SETI@home project, which uses idle time on home computers to analyze vast amounts of radio astronomy and other data in the search for extraterrestrial life.

With the advent of smart mobile devices, the ability of citizens to provide and analyze data has grown exponentially. Smart device apps now allow individuals to report severe weather events, earthquakes, and crimes. And of course, social media itself is an amazing mechanism for gathering information, in real time, regarding virtually anything conceivable that might be happening, including public attitudes toward events that can be studied by social scientists. Not everyone can be or needs to be a researcher, but today, virtually anyone can be involved in research.

Even those not formally involved in research apply research methods in everyday activities. That is, although research methods are designed principally for application to formal scholarly pursuits, their roots trace back to general public interest in the natural world and curiosity about cause and effect. Consequently, the notions underlying logic models and procedures used in all research methods are extremely valuable for nonresearchers as well, particularly in the context of critical thinking skills applied to daily life. In other words, you don't have to be a researcher to apply concepts found in research methods, such as inductive and deductive reasoning, and chances are you already are applying them and may not even know it!

For example, we are bombarded on a daily basis with all manner of news and information about national and world affairs, such as the economy, national security, health care, racism, violence, politics, inequality, bias, and many others. Making informed judgments, and not relying solely upon information fed to us, requires critical thinking skills embodied in research methods. Indeed, the Internet, and new policies in open data access (section 11.2), afford each of us unprecedented opportunity to gather data and information that *we* can independently, and personally, assess. In other words, we can test *our* own ideas and hypotheses, answer questions *we* have, and arrive at our *own* judgments and theories concerning cause and effect in the world around us. And we can do so ethically, factually, and with confidence that our results have been arrived at rigorously, not by quick reaction rooted in emotions or uninformed judgment. However, as noted in section 11.2, open access policies are not without their challenges, as clearly became evident in the COVID-19 pandemic.

4.7 Reproducibility, Reliability, and Replicability of Research Results

Foundational to the scientific method is the notion that research results should be reproducible or independently verifiable. Why? Because research and creative activity are the vital foundation of innovation in areas ranging from health care to aviation, and because most research builds upon work conducted previously. If that prior work cannot be reproduced or replicated—that is, the results verified and trusted—then the starting point for future work becomes problematic. In the case of drug design, for example, the ability of a pharmaceutical company to reproduce results obtained in a university laboratory is absolutely essential for developing commercially available therapies.

Although reproducing research results sounds simple, it is actually quite complex (e.g., see Open Science Collaboration 2015 and National Academies of Science, Engineering and Medicine 2019 in the references). Also, it is not so much a single activity to be performed but rather a continuum of activities and procedures that vary by discipline. Unfortunately, the lack of reproducibility sometimes is conflated with research misconduct (chapter 10), with the mistaken notion that research results which are not reproducible are either flawed or arrived at by unethical means. Such is the case in some circumstances; however, reproducibility does not necessarily imply correctness of the results, and nonreproducibility does not necessarily imply incorrectness of the results.

The National Academies of Science, Engineering and Medicine (2019) provides specific working definitions for reproducibility and replicability and describes the complexity of the concepts and strategies for addressing them. In the context of that report, reproducibility is defined as "obtaining consistent results using the same input data; computational steps, methods and code; and conditions of analysis," while replicability is defined as "obtaining consistent results across studies aimed at answering the same scientific questions, each of which has obtained its own data."

As noted in that report, definitions precisely opposite to that just described exist in the literature. My own view of the two terms, shown in figure 4.5, is that reproducibility and replicability constitute a continuum that must also encompass the situation in which information is obtained only in publications.

At the far left of figure 4.5, it is assumed the person or persons wishing to verify previous results are given access to them, along with the actual or identical tools or methods used. With those assets, the original researcher can try to replicate the results, someone else can try to do so, or someone else can try to do so using similar but not identical tools. Proceeding to the right, verification is attempted by being given access to the original results but using completely different tools, such as different statistical tests or computational models. And then on the far right, one is not given access to the original data or results, but

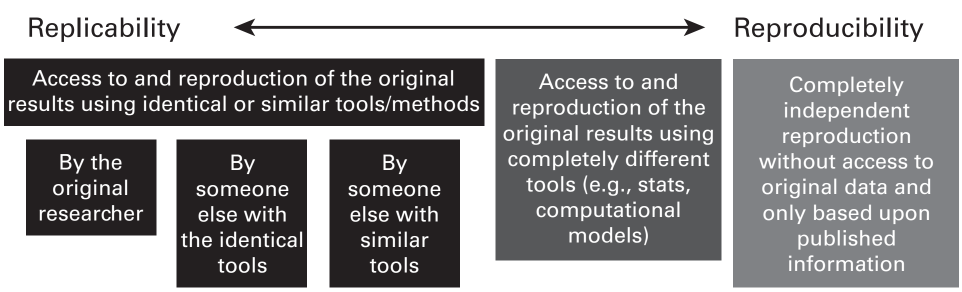

Figure 4.5
One view of the spectrum of replicability and reproducibility. A report by the National Academies of Science, Engineering and Medicine (2019) provides a working definition of each.

instead attempts to reproduce information contained only in a publication using different data and perhaps similar but not identical tools. And even other possibilities exist.

A wide variety of issues can lead to nonreplicability or nonreproducibility of research results. These include but are not limited to improper or ill-conceived experiment design and execution, improper collection and/or quality control of data, errors or misformulations in computer code, lack of documentation as the research is conducted, use of statistics or models that are not suited to the particular problem being studied, and the inherent nature of the problem, such as chaotic systems, where very tiny changes in parameters can lead to dramatically different results. At the present time, although no general methodological framework exists for evaluating reproducibility, community efforts have been launched (e.g., Center for Open Science; https://www.cos.io) that encourage researchers to submit their studies to be reproduced by others. Similar programs exist in the corporate sector.

Additionally, researchers in some disciplines can now “register” their research protocols and procedures, in advance of conducting the work (e.g., Center for Open Science), to demonstrate that no procedural changes were made during the study that might generate overly positive outcomes. In fact, publications from research utilizing such registration are annotated with a seal. Indeed, the federal government is encouraging some of its agencies to promote such practices, including training in study design and statistical analysis. With regard to the arts, fine arts, and humanities, some work has been done in reproducibility and replicability of results, though more is needed.

All of this may lead you to wonder why reproducibility has become such an important issue today and what can be done to address the challenges. First, today’s research problems, and the tools used to address them, are increasingly complex, especially efforts involving multiple disciplines. This complexity sometimes makes difficult the ability to reproduce results, especially in cases involving complex computer models. These models, say of the entire earth system, involve dozens to hundreds of parameter settings, few of which are available in formal publications. And even if the actual codes are available, the same code, with the same input data, can produce different results on different computers or even on the same computer using a different compiler. Likewise, data collected via surveys, or in clinical studies, can vary among populations, especially when sample sizes are small. Although research methods account for such variances, they can impede reproducibility.

Second, although the research enterprise is “self-policing” to a large extent via peer review of publications and grant proposals (chapters 6 and 7), it is not always possible, especially in complex studies, for reviewers to spot problems in methodology, or be fully informed about the details of tools and data used, because publications and proposals are necessarily limited in length. Traditionally, a publication had to contain sufficient detail to afford reproducibility, but that simply is not always possible today. Consequently, the open science framework, and related open access policies (chapter 11), are making available all data and related materials, such as computer codes and settings, used in producing results presented in formal publications.

Third, some concern exists that reproducibility can be impacted negatively by the pressures researchers face to publish their findings, and especially to publish only positive results (chapter 8). This has led some scholarly publications to require reproducibility as a criterion for accepting a submitted manuscript. Additionally, in evaluating their scholars, academic institutions are being encouraged to emphasize not the number of articles published but rather the quality and impact of those publications.

Fourth and finally, a notion that has gained traction—including within congressional legislation—is that an inability to reproduce research results somehow suggests the presence of research misconduct. However, as noted previously, such is not necessarily the case.

Given these and other issues, what can be done and what is being done regarding reproducibility of research results? First, all researchers should be formally trained in experiment design and application of research methods. In many disciplines, including my own, such is not the case today. Second, online courses are now available, as are federal resources, to acquaint researchers with the issue of reproducibility of results and steps that can be taken to ensure it is applicable. Third, as noted previously, ready access to data, computer codes, and other aspects of a study, via open access frameworks now being put in place (chapter 11), will help considerably with reproducibility. Fourth, community efforts now exist, in the open science enterprise, to which researchers can submit their results for independent verification. Fifth, an increasing number of publications, especially in certain fields of social and behavioral science, are now requiring a demonstration of reproducibility prior to article publication. Sixth, incentives in academia for publishing are shifting to publishing quality instead of quantity. And finally, many studies are being undertaken to understand why certain research results are not reproducible. Chapter 9 addresses ethical guidelines and best practices that can contribute to the reproducibility of research results, and additional information on reproducibility can be found in the references noted previously.

Ultimately, addressing the issue of reproducibility of research results is a team sport, with many organizations and sectors of the community being involved. Interesting challenges arise in the context of research conducted within industry which, owing to proprietary considerations, usually cannot disclose results broadly (chapter 12). This begs the question as to whether research results produced within industry can be reproduced or replicated by others on the outside. As a result, emphasis on reproducibility is likely to continue for some time. If done thoughtfully, it will strengthen the credibility and increase the value of research in the eyes of all.

4.8 Surprise, Surprise! Serendipity in Research and Creative Activity

Around twenty-five years ago, I served on a multidisciplinary panel to review roughly a dozen research proposals submitted to a federal agency. The proposals were rather special because, with budgets up to $50 million each, they sought to establish major research centers in various topics of science and engineering. In painstakingly discussing each proposal, my review panel colleagues and I came to one that several in the room criticized with notable vigor. Although none of the critics were deep subject matter experts in the work being proposed, they raised insightful and valid concerns. I too had questions but was the lone voice of support for funding the proposal, partly because I had a deeper understanding of the work being proposed, but also because some of the arguments against the proposal were based upon understandably incorrect assumptions made by my fellow nonexpert panel members. As an expert in the field who knew the facts, I was able to explain why the assumptions they made were incorrect. Ultimately, the proposal was funded and the resulting center became a resounding success. The moral to this story has two parts.

The first is that I seemed to have been in the right place at the right time. But more importantly, my participation was a fluke. In reality, I was a last-minute substitute for another reviewer who became ill shortly before the review panel met. The person I replaced, like the other reviewers, was not an expert on the topic of the proposal under consideration. As a result, in all likelihood, the proposal would not have been funded, and the center would not have gone on to do transformative science, had I not been added at the last minute. Serendipity prevailed.

Perhaps you have had similar experiences. Maybe you have found yourself saying, after something positive happened in your life, "What are the odds of *that* occurring?" This begs the question of how one defines serendipity. Generally speaking, it is an unanticipated positive or valuable development. That is, serendipity is something that cannot be predicted or orchestrated.

The word itself was coined in 1754 by Horace Walpole, who was the son of Britain's first de facto prime minister. Walpole described serendipity as "the faculty of making happy and unexpected discoveries by accident"

(Interesting Literature n.d.). As you can see, Walpole viewed serendipity as requiring action on the part of the fortunate recipient via use of the verb "making." He also noted that serendipity leads to inherently positive outcomes. And interestingly, the definition includes the notion of discovery, so it automatically encompasses research and creative activity. Yet, serendipity has much broader application.

For example, serendipity is a popular foundation for movies. In *The Parent Trap*, for example, two identical twins separated early in life attend the same summer camp, completely by chance, and discover they are in fact sisters. After considerable mischief that causes their father's fiancé to run away screaming, they lead their divorced parents to reunite. This example has all the attributes of serendipity; that is, chance, discovery, and a positive outcome. And who can forget the fact that Spiderman's powers came about when an ordinary person, quite by accident, was bitten by an irradiated spider? Those who love the movie *Sleepless in Seattle* will recognize serendipity occurring multiple times throughout the story.

A great deal has been written about the role of serendipity in our lives. How much of what happens to us really does occur by chance? Do *we* play any role, as Walpole would suggest? How do we really know if chance is the explanatory factor? These and many other questions are interesting to ponder and can quickly lead to fascinating and deeply philosophical conversations, even delving into various religious beliefs. Interestingly, you may not be surprised to know—and you can confirm this with a simple web search—that the word "serendipity," apart from referencing a movie having the same name, is associated with discovery research.

As described throughout this book but especially in this chapter, the process of research and creative activity always begins with a purpose; with goals; with a set of questions; and often, with a hypothesis. Frequently, we have a sense of the results in advance, though research methods require that we arrive at findings and conclusions through rigorous processes that may well prove our instincts wrong. And indeed, sometimes things do not turn out as we expect. We obtain negative results. We see unexpected or counterintuitive behavior. Or we stumble onto something truly amazing that could never have been anticipated.

I prefer to conceptualize this notion as a flowing river, the center of which—the fast-moving part—represents the main goals of a research project. They have our attention—they are where our hypothesis lies, and where most of our intellectual energy is expended. However, away from the center of the river, one finds little whirls, sometimes near the shore, that go almost unnoticed. Yet they are fascinating in their own right and would not exist without the fast-flowing water. It is these little whirls I liken to unexpected results or accidental discoveries that potentially are transformative. The trick is knowing whether a little whirl is just an interesting sidelight or something that warrants further exploration. During a lecture at the University of Lille in 1854, Louis Pasteur famously said, "In the fields of observation, chance favors only those minds which are prepared" (Peterson 1954, 473). Not only do our minds need to be prepared for the unexpected, but we need to be willing to take time to explore it.

Many important and surprising discoveries have been made by accident, and they occur in all disciplines. How many discoveries? How often do they occur? Those are difficult questions to answer, but in some respects, surprises occur in every research and creative endeavor. However, those we ascribe to serendipity are of a special type that share three important characteristics: First, they were not planned and could not have been anticipated; second, they ultimately led to something positive or beneficial, usually with broad recognition and utilization by society; and finally, they were not foundational to the original ideas being explored, though could not have occurred without them.

Numerous examples of serendipitous research discoveries exist, and I will examine only a few in detail here. I hope you are sufficiently intrigued to explore others on your own, so for starters, you may wish to explore the origin of aspartame, chaos, saccharin, weather radar, Viagra, radioactivity, the atomic nucleus, X-rays, Post-It notes, microwaves for cooking food, corn flakes, the match, atomic fission, super glue, dynamite, Velcro, the Slinky, vulcanized rubber, and famous, almost priceless paintings that remained hidden for centuries because someone painted over them.

One of the best examples I know is penicillin. Many of us know the story, and today, the word "penicillin" represents a group of both natural and semisynthetic antibiotics that prove very effective at defeating a wide array of staph and strep bacterial infections. Penicillin was discovered by accident in London in September 1928, when Alexander Fleming, a Scottish biologist, was studying staphylococci bacteria. The bacteria had been smeared in several covered petri dishes, after which Fleming left for summer vacation. Upon returning, he noticed that one of the Petri dishes was open to the air and had been contaminated by a blue-green fungal mold called *Penicillium notatum*. Interestingly, no bacteria could be found near the mold—it had been killed by it. Many years and tests later, the drug penicillin was approved for human use and today is termed the "wonder drug," though some bacteria have developed resistance to it owing to its extensive repeated use.

As a meteorologist, my favorite example of serendipity in research concerns chaos, because it is believed to place fundamental limits on our ability to predict weather. The father of modern chaos theory, or at least the rebirth of that theory, as has been noted in recent work, is the late Massachusetts Institute of Technology professor Ed Lorenz—whom I had the extraordinary privilege of meeting. Borrowing from Dizikes (2011), the year is 1961, and it is winter.

Professor Lorenz had developed a highly simplified model of the atmosphere, containing twelve variables such as wind speed and temperature, which he then coded into a computer. As the machine was churning out numbers, Lorenz left to get a cup of coffee. This particular calculation was actually a repeat of one he had performed earlier, but in those days, computers did not have the sorts of storage devices that are commonplace today. Thus, upon returning from his break, Lorenz started the recalculation by typing in numbers from a printout of the earlier one, though in so doing, he chose to round one of the variables to three places instead of six. That is, he typed in 0.506 instead of 0.506127. What he discovered, after the calculation had proceeded for two months of simulated time, was nothing less than astounding.

Specifically, the results were completely different from the previous experiment, when in fact he believed they should have been identical. This led to what we know today as "sensitive dependence to initial conditions," which means a tiny change in the starting point of calculations involving chaotic dynamical systems can lead to dramatically different outcomes.

As a practical example of Lorenz's discovery, the tiny wind fluctuations created when a butterfly flaps its wings could, theoretically, induce changes in global weather patterns two weeks later. This finding—the so-called "butterfly effect," literally transformed the science of mathematics and many other fields, including meteorology. It also has very important implications for the reproducibility of research results, which was addressed earlier in this chapter and also is discussed in chapter 9.

I am sure most of you have had an X-ray at some time in your life, and the discovery of X-rays is a fascinating story. In 1895, German physicist Wilhelm Roentgen was experimenting with cathode ray tubes, like old-style television tubes or the sorts of tubes one finds in an oscilloscope. When the tube was energized, Roentgen observed a glow in a dark office nearby. Realizing radiation was involved, but not knowing the type, Roentgen called the effect X-rays. It was obvious to him the rays were impervious to solid objects, like walls, and Roentgen is said to have taken the first medical X-ray by subjecting his wife's hand to the strange radiation. Today, X-rays and derivatives from them have transformed the fields of medicine, engineering, and astronomy, to name but a few.

Considering these three examples, and others provided in the references (e.g., McClellan 2005; Eisinger 2013; Ward 2015), you will find they meet all three criteria for serendipity mentioned previously; namely, they were discovered by accident, made positive contributions, had wide impact, and were linked to but not foundational to the work originally being performed. As a scholar, I hope you always give place to the possibility and value of serendipity in the work you perform, though being careful to not chase every interesting sidebar that might come your way. Knowing when an unexpected development may be significant is difficult, so as I repeat throughout this book in multiple contexts, if you are uncertain about something, ask! Research and creative activity are team endeavors by virtue of the scholarly community to which you belong, even if you are working mostly on your own. Never hesitate to seek counsel from others. You never know if such a conversation will lead to a serendipitous outcome!

Assess Your Comprehension

1. List key properties of all research outcomes, irrespective of discipline.
2. Describe the two broad categories of research methods.
3. What is empirical research?
4. How does deductive research differ from inductive research?
5. How does independent research differ from directed research?
6. Describe the steps of the scientific method.
7. What is a hypothesis and how is it used in research and creative activity?
8. What is a theory and how does it differ from a law in the context of research?
9. Describe the historical research method.
10. What is source criticism?
11. Describe some of the problematic issues associated with Indigenous research.
12. What are the key principles by which Indigenous research should be performed?
13. What is the difference between explanatory scope and explanatory power?
14. Describe the relationship between education and research.
15. What is discipline-based education research and what tenets does it share with Indigenous research?
16. What is citizen science and how is it applied?
17. What is reproducibility of research results and why is it important?
18. Why has the issue of reproducibility of research results become so important?

19. In what ways do reproducibility, replicability and reliability of research results differ from one another?
20. How can nonreproducibility of research results be mistakenly conflated with research misconduct?
21. What factors can lead to research results being nonreproducible or nonreplicable?
22. What actions can be taken to improve the reproducibility of research results?
23. Define serendipity and the role it plays in research and creative activity.
24. What three criteria are associated with serendipity?
25. List a few examples of innovations that trace their origin to serendipitous outcomes from research.

Exercises to Deepen Your Understanding

Exercise 1: Choose a research problem of interest, perhaps one from a different exercise, and apply the scientific method to frame it. Begin by describing the problem and your motivation for selecting it, form the hypothesis, and then proceed to apply subsequent steps of the scientific method to describe how you would go about testing the hypothesis. Identify road blocks that might occur and ways in which you might be tempted to alter your hypothesis, during the research, to obtain better outcomes—and the negative consequences, including with regard to ethical principles, of doing so.

Exercise 2: Anyone can become involved with research—even nonexperts—via citizen science. For this exercise, choose a research project of interest from the lists provided at the links shown below and put yourself in the position of citizen volunteer. Describe your interest in the project, any specific expertise you bring to it, your reasons for choosing it, and how you would go about providing data or otherwise participating in the project. In some cases, you can actually participate in the project online, and if you choose such a project, describe your experience. Did your views regarding citizen science (e.g., value, effectiveness, rigor) change after completing this exercise?

- https://www.scientificamerican.com/citizen-science/
- https://www.zooniverse.org/projects

Exercise 3: Reproducibility, replicability, and reliability of research results increasingly are important not only in research, but also to other stakeholders, especially when research results are utilized in setting public policy. Identify a few research problems for which the results tend to be reproducible, as well as a few for which they tend to be not reproducible. Describe the reasons for this behavior and potential implications for research itself, the application of research outcomes to policy, and perceptions that nonreproducibility is essentially synonymous with poor experiment design or nefarious behavior on the part of researchers.

Exercise 4: Some of the world's greatest discoveries and technological breakthroughs occurred mostly or exclusively by chance. Identify one or more examples, similar to those provided in the chapter, and trace their evolution, including their impact on society. What other positive or ancillary benefits or developments occurred (sometimes referred to as "spillover") as a result of the serendipitous discovery, and how do they compare to the primary benefits? You also may wish to consider discoveries or research advances that have occurred exclusively as a result of the COVID-19 pandemic and conjecture about their future impacts on society.

Exercise 5: In order to gain deeper insight into methods used by various disciplines in scholarly activities, select three disciplines, all very different from your own, by exploring academic colleges and departments at your institution. For example, if you are a journalism major or scholar, you might select electrical engineering, finance, and geophysics. If you are a physics major, you might select musical theatre, French, and psychology. Develop a single set of questions regarding research methods and conduct interviews of the department chairs in them. Your questions should focus on the key topics described in this chapter—namely, broad research frameworks used, gathering of data or making observations, hypothesis generation as appropriate, analysis or synthesis of data, modeling or testing (for example, dance majors test their hypotheses in studios), synthesis of results, and presentation of new knowledge created. Compare and contrast all three sets of disciplinary approaches, identifying commonalities as well as distinct differences. Do you feel the disciplines would benefit from knowing about and sharing their approaches with one another? If so, what specific elements would be beneficial in doing so, and what benefits would be realized?

Exercise 6: Read the papers by Snow et al. (2016) and Dawson et al. (2017) on Indigenous research methods in the references and describe ways in which your own research could engage Indigenous communities. What community or communities would be most appropriate, and how would you go about learning of their culture, approaching them with your ideas or research questions, building relationships, and engaging them in collaborative work that would both create new knowledge and bring value to them? Describe the value proposition for them as you see it now.

The MIT Press would like to thank the anonymous peer reviewers who provided comments on drafts of this book. The generous work of academic experts is essential for establishing the authority and quality of our publications. We acknowledge with gratitude the contributions of these otherwise uncredited readers.

This book was set in Times Roman by Westchester Publishing Services, Danbury, CT.

Library of Congress Cataloging-in-Publication Data

Names: Droegemeier, Kelvin, 1958– author.
Title: Demystifying the academic research enterprise : becoming a successful scholar in a complex and competitive environment / Kelvin K. Droegemeier.
Description: Cambridge, Massachusetts : The MIT Press, [2023] | Includes bibliographical references and index.
Identifiers: LCCN 2022062131 (print) | LCCN 2022062132 (ebook) | ISBN 9780262547079 (paperback) | ISBN 9780262377218 (epub) | ISBN 9780262377201 (pdf)
Subjects: LCSH: Universities and colleges—Research—United States. | Research—Moral and ethical aspects—United States. | Research—Methodology. | Learning and scholarship—United States.
Classification: LCC LB2326.3 .D76 2023 (print) | LCC LB2326.3 (ebook) | DDC 378.0072—dc23/eng/20230512
LC record available at https://lccn.loc.gov/2022062131
LC ebook record available at https://lccn.loc.gov/2022062132