Error Types

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Errors in science range along a spectrum from those relatively local to the phenomenon (usually easily remedied in the laboratory) to those more conceptually derived (involving theory or cultural factors, sometimes quite long-term). One may classify error types broadly as material, observational, conceptual or discoursive. This framework bridges philosophical and sociological perspectives, offering a basis for interfield discourse. A repertoire of error types also supports error analytics, a program for deepening reliability through strategies for regulating and probing error.

Nothing's concluded until error's excluded.
—Prospective Proverb

1. Introduction

Error[1] is common in scientific practice (Collins and Pinch 1993; Darden 1998; Allchin 2000*a*). But pervasive error threatens neither the search for trustworthy knowledge nor the epistemic foundations of science. Far from it. Rather, past error—properly documented—is a form of negative knowledge. As such, it may even productively guide further research. The history of science, as compiled hindsight (Darden 1987), includes epistemic caveats (as methodological standards) for designing experiments, interpreting results and constructing effective scientific institu-

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1. By 'error', I mean broadly any mistaken conclusion or unintended outcome in science or technology (see §2 below for a more formal characterization serving the purposes of this paper). Error becomes manifest as additional work, where scientists must "undo" or redo a series of experimental procedures or steps in their reasoning. In this paper, my concerns do not intersect with several technical uses of the term 'error'. I do not discuss *measurement error,* in the sense of precision or tolerance of numerical data. Nor am I concerned with the statistician's *standard error,* the deviation from or confidence interval about a sample's mean value.

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tions. Simply, scientists endeavor (ideally) not to make the same mistake twice. One significant task of science, then, is to identify and catalog potential errors (Allchin 1999).

Many errors are field-specific. Only biologists, for instance, consider whether model organisms may not adequately reflect human physiology. Only high-energy physicists worry about improper energy cuts in interpreting the existence of subatomic particles. Accordingly, scientists assemble, mostly informally, domain-specific *error repertoires* (Mayo 1996, pp. 5, 18). However, one may also analyze errors across fields and look for informative patterns. That is, one might fruitfully apply a principle of general theory types (Darden and Cain 1989; Darden 1991, pp. 248–251) to the context of characterizing errors. In this paper I describe a taxonomy of notable error types in science and a framework for organizing them.

Mayo has already introduced briefly the notion of standard, or paradigmatic, mistakes, which she calls *canonical errors* (1996, pp. 18, 51 n.17, 150, 453–54). She identifies four types (p. 449):

(1) mistaking chance effects or spurious correlations for genuine correlations or regularities;
(2) mistakes about the quantity or value of a parameter;
(3) mistakes about a causal factor; and
(4) mistakes about experimental assumptions.

But (as Mayo herself notes) this short list is hardly exhaustive. My primary aim here, then, is to expand this list and to provide a framework for thinking about its completeness more systematically (§2 below).

My work also follows in the spirit of Hon (1989), who advocated appropriate epistemological categories for error. Hon argued that such mathematically narrow distinctions as random versus systematic error were not sufficiently informative. However, while Hon focused just on experimental error, my scope here is much broader. I address conceptual errors, as well as some related to the cultural dimensions of science. My conclusions also resonate with Star and Gerson's (1986) sociological characterization of error as an interruption to work flow. Here, the behavior of scientists reflects epistemic practice (§2).

Errors can occur, of course, at many steps of scientific investigation, inference, or communal discourse. Experimentalists, for example, frequently talk about "sources of error" in their apparatus or test design. My intent is to broaden this notion to include other aspects relevant to reaching scientific conclusions. Sources of error range from such simple mistakes in the lab as using impure samples or uncalibrated instruments, to such complex or culturally embedded problems as gender or class bias and outright fraud.[2] Attending to error thus engenders a perspective of exceptionally broad scope. Each error identifies a factor—whether experimental, conceptual, or sociological—that is critical to developing (or "constructing") reliable knowledge. By spanning such divergent domains, a complete typology of error can serve as a significant structure for unifying science studies (§4 below).

Elucidating error types contributes to a more complete descriptive portrait of scientific practice, of course. Yet analysis of errors may also deepen normative epistemic understanding, as well. Lack-of-function studies (e.g., Bechtel and Richardson 1993, pp. 18–20) indicate conversely the elements of an effective process. Deficits and "failures" can reveal indirectly how we ascertain fact. Each identified error type may thus correspond to a methodological parameter critical to science, where science is viewed as an endeavor to build reliable (that is, trustworthy, relatively error-free) knowledge (Ziman 1978).

One result of analyzing error types in science is a catalog of apparent handicaps and limits in science. Errors may thus seem to threaten the authority of science. One response seems defensive. Some cast certain errors as "symptoms of pathological science," excluding them from science proper, thereby preserving its perceived integrity (Langmuir 1989; Rousseau 1992; Dolby 1996). But these efforts amount to little more than semantic gerrymandering: error still exists and shapes the scientific enterprise. Others respond more cynically by rejecting scientific authority outright (Collins and Pinch 1993). By legitimating all errors, they succumb to an impotent epistemological nihilism. From another perspective, however, one may hope to remedy epistemic problems by averting or accommodating error. Pragmatically, someone might learn how to differentiate an error from an ultimately reliable claim. Articulating error types can help in establishing methods for addressing the errors, viewed as fixable problems rather than as inherent flaws. In my view, we should refrain from bemoaning our epistemic handicaps and, instead, develop strategies to cope with them. This epistemic posture is the foundation of the program called *error analytics.*

The program of error analytics holds promise in several ways (§3 below). First, scientists may try to prevent or reduce certain types of error. (In many cases, they already do—and we may document and assess their methods.) Second, when they encounter anomalies, a framework of error

2. On impure samples, see Latour and Woolgar (1979, p. 169) for a case of unknown selenium in water; see Rousseau (1992) on polywater. See Franklin (1997) on calibration. On cultural and gendered science, see Haraway (1989). On fraud see Broad and Wade (1982) and below.

types may help guide them in diagnosing and localizing the latent error (Darden 1991, Chaps. 8, 12, 15). Third, in cases where an error type seems ineliminable, researchers may seek mechanisms for detecting such errors and accommodating them. Finally, scientists may deepen reliability in the absence of any explicit anomaly by probing for possible, yet undetected errors (Mayo 1996). Deliberate, proactive search for specific error types would complement the process of anomaly resolution. Ultimately, epistemicists (philosophers and sociologists alike) might identify "checkpoints" where historical experience warrants review of particular error types. In all these cases, a repertoire of error types can support scientific practice, especially if integrated into the education of emerging scientists (Petroski 1994; Hall and Darden, forthcoming). We might thereby profitably learn from our past mistakes.

2. A Spectrum of Error Types

Specifying a type of error in science means identifying, conversely, an epistemic step critical to producing reliable knowledge (Ziman 1978). Fully realized, the task of error analytics is substantial. To organize this project I begin with a taxonomy of general error types (Figure 1):

The errors are arranged in two overlapping ways. First, the foundational dimension follows a path from phenomena in the world to the facts and theories about them, all the way through their sites of cultural application. One may easily conceive science as "mapping" some aspect of the physical world, whether to represent it abstractly or to shape it technologically. In the widely used map metaphor (Ziman 1978; van Frassen 1980; Judson 1981; Turnbull 1989; Giere 1998), the phenomena are the territory. Scientists develop a series of maps and indirect maps. They formulate maps *of* maps in successive layers. Nevertheless, all rely on a collection of initial observational benchmarks (where observation is widely construed as data collection). Each mapping or subsequent transformation (taking into account its intended domain) is subject to error.[3] *An error is a faulty mapping that does not preserve the structure of the world as intended* (see Hacking 1984, pp. 208–209; Allchin 1998).[4] Maps may thus be arrayed along a

3. Maps—like models—are selective and embody conventions of representation (Turnbull 1989). These features can be among the sources of error, as critics of the map metaphor note (Sismondo and Chrisman 2000). That is, error can emerge if one misinterprets the scope or perspective (relevant features) of a given map or fails to recognize its modes of representation, even if the mapping proper is "correct." While these elements are often transparent in scientific discourse, I include them (for the sake of discussion) in my characterization of a complete mapping.

4. My primary aim is not to *define* error, but to sort features of an epistemic process. Still, it may be useful to recharacterize error in other idioms of expression. For example, in

ERROR TYPES

LOCAL

DERIVED (GLOBAL)

Material
- **improper materials (impure sample, contaminated culture)**
- **improper procedure (experimental protocol violated, poor technical skill)**
- **perturbation of phenomenon by observer (placebo effect)**
- **failure to differentiate similar phenomenon through controlled conditions**

Observational
- **insufficient controls to establish domain of data or observations**
- **incomplete theory of observation (instrument/protocol not understood)**
- **observer perceptual bias ("theory-laden" observation, need for double-blind)**
- **sampling error (statistical rarity, weak significance level cutoff or other probablistic factors)**

Conceptual
- **flaw in reasoning (includes simple computational error, logical fallacies, mistaking correlation for causation, incomplete evidence)**
- **inappropriate statistical model**
- **inappropriate specification of model from theory**
- **misspecified assumptions or boundary conditions**
- **theoretical scope (domain) over/undergeneralized**
- **incomplete theory, lack of alternative explanations (limited creativity)**
- **theory-based cognitive bias, entrenchment**

Discoursive
- **communication failures: incomplete reporting, obscure publication, translation hurdles, patchy citation/search system**
- **mistaken credibility judgments (Matthew effect, halo effect) / fraud**
- **unchecked sociocultural cognitive biases (gender, ethnicity, economic class, etc.)**
- **breakdown of systems for credentialing scientific expertise**
- **public misconception of scientific results and misunderstanding of science (poor science education, poor science journalism, etc.)**

Figure 1. Taxonomy of error types, arranged along a specturm from events and claims that are relatively local to the phenomena being studied to those relatively more derived, or global.

spectrum, or scale, from *local* to *derived,* reflecting the layers of transformations from the original world. As maps are reinterpreted and compounded into meaningful patterns, they inevitably tend to incorporate or rely on a broader base of observational benchmarks. Interpretation occurs, for example, in the context of other observations. A method for transforming

terms of conventional philosophical views of knowledge, errors may involve either unwarranted justification, false claims, or faulty belief. Errors fit an odd philosophical space because being in error implies not knowing about the error. *Known* errors (those clearly identified as error) are, essentially, no longer errors, as identifying them involves a change one map into another of "equivalent" structure relies on another body of evidence. Thus, as maps become more derived they also become more *global.* The local-derived scale thus stretches from particular facts to general ideas. It also fits, sociologically, with the lengthening and expansion of networks through "centers of calculation," as noted by Latour (1987, pp. 80–83, 210–57). Errors, accordingly, may be characterized along a local-derived, or local-global, spectrum. The spectrum is a framework for assessing the completeness of a taxonomy of error types, as well as for probing for error in any given instance.

This spectrum has important implications for interpreting and remedying errors. Local errors typically involve circumstances in the laboratory or the field that define the phenomenon. There are relatively few contingencies, or variables, that might yield an alternative fact or product (within a given conceptual framework). As the scope of observations increases at more derived, or global, levels, however, so too will the number of contingencies. Local errors should thus be relatively easy to identify and remedy. More derived, or global, maps will tend to be more diffusely grounded and errors harder to ascertain.

The second overlapping scheme for organizing error subdivides the local-derived spectrum, while connecting the epistemic process to scientists' practice. Here, one may classify errors into four broad types (each elaborated more fully below, §§2.1–2.4): (1) material errors; (2) observational errors; (3) conceptual errors; and (4) discoursive errors. Material errors involve physical aspects of getting the phenomenon "right," where investigators have a role in creating the phenomenon. Observational errors concern methods of perception and data collection, connecting the territory to the first map (the interface of phenomenon and data). These include the problem of framing observation on the appropriate phenomenon

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in the status of belief. By contrast, incipient errors have not yet been characterized as false, unjustified, or mistaken and thus cannot be construed in context as error. Hence, an individual cannot know about error except through retrospective attribution. For simplicity, I focus on whether claims are true, in the sense of faithful representations. Thus, false maps or models *known* to be false (and sometimes used as an investigative tool) do not constitute error. Nonetheless, we may classify them as potential error due to the critical element of interpretation, or belief. Because maps, like models, are both selective and conventional, they cannot be completely true. One must consider both their intended functions and the inherent complexity of representation in regarding them as error (see note 3).

Errors may also be characterized in the experimentalist idiom. Errors are facts (mis)interpreted as artifacts (or vice versa). Alternatively (in a sense more apt to technology), one may view error as any element generating "incoherent" practice. The mapping metaphor is still central (Hacking 1984). I trust my taxonomy of error types can accommodate various ways of characterizing knowledge.

(discussed further below). Conceptual errors involve the large body of theoretical interpretations and manipulations, widely familiar to philosophers. Discoursive errors encompass aspects of discourse—namely, communicating, assessing, and regulating conceptual maps among a community of researchers, as well as to others who hope to rely on scientific knowledge. Each error type thus corresponds to a particular form of practical remedy: a change in procedure or materials, a change in observational methods, a change in concepts, or a change in interpersonal actions.

These four categories largely parallel Star and Gerson's (1986) sociological taxonomy of anomalies as: mistakes and accidents (1), artifacts (2), discoveries (3), and improprieties (4) (though not all discoursive errors are fraud). Hon (1989) also proposed similar categories, although his organizing principle was the chronology of an investigation (p. 498), rather than its epistemic structure. He linked material errors to theory (experimental design or assumptions) and cast errors about background theory as preliminary. The convergence of classification schemes from experimentalist, sociological and more general epistemic perspectives suggests that these four general error types are fairly robust. As noted, they also seem to align with particular dimensions of scientists' practice.

2.1. Material Errors

Consider, then, how various error types fit in this organizational framework (Figure 1). The first layers of error are material and involve generating a particular phenomenon that a researcher has decided warrants observing. A scientist reviewing a published research report for possible error, for example, generally first examines the "Materials and Methods" section. Did the researchers actually observe what they intended to or claimed to observe? An impure metal, a contaminated bacterial culture, or an unrinsed sample, for example, can yield a misleading signal that may not represent the intended target of observation. A first error type, then, is materials that are not precisely characterized and produced. Experimental protocol is equally important. For example, failing to keep a specimen chilled, adding a reagent too late, leaving lights on in the greenhouse, or finding that deer trampled plants in a study plot can all potentially discredit the resultant observation or data. Consider Millikan's careful analysis during his classic measurements of electron charge, allowing him to discount several events due to improper experimental conditions (dust, air currents, etc.; Franklin 1986, pp. 140–57). Proper protocol is determined, of course, through experience. While "correct" procedure is wholly a convention, it reflects what researchers have determined produces consistent and relevant results in a given context. One may question the protocols themselves (especially when first being developed), but from a more global position. Where researchers do agree on proper protocol, following it can be essential in producing the relevant phenomoenon. Thus, experimental or "craft" skills, as emphasized by the Bath School (Collins, Pinch, Schaffer, etc.), are important. Dirty glassware and inept lab technicians can be local sources of error, each exemplifying a simple error type.

In some cases the experimenter or observer may inadvertently *alter* the phenomenon being observed. An ostensibly natural structure—bacterial mesosomes, for example—may be due to the experimenter's procedure (Allchin 2000*b*). It is an *artifact.* One familiar example is the placebo effect, whereby a patient responds to the investigator's cue of a possible remedy. Here, of course, researchers now know (through historical experience) how to cancel the error (through blind studies). Many error types are marked by such well known compensatory strategies. Error analytics aims to articulate, develop and hone such strategies. Material errors generated by observer perturbation may well be detected only through higher level (more global) analysis. But the source of error is working with an identifiably "wrong" phenomenon.

Finally, a phenomenon may be in "error" because experimental conditions fail to address a key, but perhaps subtle, difference between two quite similar phenomena. That is, material control of a critical variable may be missing. An observer will be unable to *resolve* or differentiate the two phenomena, and potentially mistake one for the other. In some cases, the investigator may not understand (at a more global level) the relevance of the variable or be able to control the difference experimentally. In other cases, there may be instrumental limitations. In either case, the result is, again, examining the "wrong" phenomenon.

These types of local errors, one trusts, are easily found or prevented, perhaps contributing to an impression that they are not epistemically significant. But they are a major concern and topic of discussion among researchers in a lab or at a field site. Labs and research groups develop reputations based on whether they are prone to or escape such errors. Good lab/field skills and alert experimentalists are a first, even if commonplace, method for regulating error in science. They are not epistemically trivial. In accord with the recent renewed interest in experimentalism, philosophers and sociologists of science need to articulate and investigate these factors more fully. Error analytics helps to highlight the role of such familiar, virtually invisible features in shaping knowledge.

2.2. Observational Errors

Error may next be due to the process of observing itself, where one establishes the empirical benchmarks for subsequent mappings. For example, one critical element is *framing* an observation appropriately. One can mistake one suite of signals as characterizing a particular phenomenon of interest, when it does not. Here, it is the observation that is misplaced (though the concern, as above, is focusing on the relevant phenomenon). Even where certain factors requisite for framing the phenomenon may be known, additional variables may still be relevant. Investigators often rule out error by dissecting or teasing apart these observational variables experimentally. That is, they *resolve* sets of similar, overlapping conditions by using parallel observation protocols which vary typically by only a single factor (Mill 1874, pp. 278–311). This aim guides many experimental controls, even when no theory is being tested. Researchers thereby assess the observational relevance of specific variables or, alternatively, mark the precise domain of their data (see, e.g., cases described by Rudge 1999, pp. 19–20; Galison 1987, p. 64; Franklin 1986, pp. 140–57; Mayo 1996, pp. 231–42). From an error analytic perspective, observational controls are important in regulating (in the sense of monitoring and adjusting for) error. In a simple hypothetico-deductive framework, a negative control adds nothing. It confirms no "positive" prediction. In error analytics, however, such controls perform substantive epistemic work by ruling out potential alternatives and thereby deepening reliability. Indeed, lack of controls—and the consequent possibility of error—is probably the most frequent criticism of inadequate experimental work found in scientific discourse. Philosophers of science, in my view, owe more prominent focus and depth of discussion to this central scientific practice and its role in regulating error.

Alternatively, the process of observing may itself be imperfect or not well understood, resulting in misrepresentations that go unrecognized. For example, as Hacking (1984) has noted, early microscopes were fraught with lens distortions, such as spherical and chromatic aberrations. Diagnostic tests or chemical indicators may yield periodic false positives, as well as false negatives. Again, ideally, the investigator understands how the observation process maps the phenomenon. How does it distort the image or transform the information? Intimate knowledge here allows a researcher to (depending on context) use observations selectively, modify (or "correct") data appropriately, or improve the observational instrument or method. For example, a distortion in the Hubble telescope was "undone" by additional optical devices. Uncertainty about the process of observation—for example, with a new instrument or procedure—opens the possibility for error.

Human observers are also integral to the process. They are scientific instruments, too (Allchin 1998). Cognitive limits and biases are thus inescapable (Bechtel and Richardson 1993, pp. 3–16; Sunderland 1992). Theory-laden perception is normal. Still, while such bias can lead to error, one may search for and counteract it (e.g., double-blind studies that eliminate the factor of observer bias). Cognitive bias need not threaten credibility in science. One merely needs to be aware of it and apply a system of checks and balances. This general epistemic posture of reinforcing reliability by reducing error helps motivate the program of error analytics.

Finally, I include sampling error and its statistical variants as observational errors. The challenge is knowing whether a population of measurements (sometimes of a probabilistic phenomenon), when viewed statistically, counts as a "genuine" observation. Error may lurk in an unrepresentative sampling of the phenomenon. In a sense, analysis of observations or data has already begun at the conceptual level here. At the same time, a primary aim of assembling a statistical "map" is to check whether the observations can even be considered a legitimate benchmark for further conceptual interpretation.

2.3. Conceptual Errors

Many further error types "downstream" derive from perfectly accurate observations. These include: inappropriate statistical models, unwarranted experimental assumptions, misspecified boundary conditions, cognitive bias due to theoretical entrenchment, cryptic theoretical alternatives, and flaws in reasoning, such as computational error and the classic failure of induction (Figure 1). Philosophers have already characterized well these conceptual, or interpretive, errors (e.g., Kosso 1992) and no further elaboration is needed here. Still, one may note that while one cannot eliminate many such errors, one can often remedy them. For example, critical exchange between advocates of discordant theories (at the level of discourse) can help expose the role of contrasting theoretical commitments and lead to resolving evidence more finely to test their different implications.

One error type does deserve wider consideration by philosophers, in my view: errors of scope, or specified domain (Lakatos 1976, pp. 13–42; Darden 1991, pp. 269–75). That is, scientists sometimes err by assuming or promoting too broad a range of application (domain, or territory). In such cases, the critical issue is not whether some rule, law, claim or model is true or false (even probably so), but under which precise circumstances it holds and does not hold. One circumscribes interpretations of scope or domain that would otherwise lead to error. In some other cases, scientists advocate alternate, conflicting theories whose explanatory scopes overlap. They often cast the alternative as error. Indeed, notions of theory competition typically imply that one theory is "right," while the other is "wrong." However, the key question may be not whether one theory is inherently superior, but how each theory is warranted in separate contexts, or domains. One may differentiate their domains to reduce error (Allchin

1997). Establishing scope involves a large set of experimental studies, or benchmarks across an empirical landscape. Hence, a domain-type error is more global in character than the local errors of experiment discussed above.

2.4. Discoursive Errors

Error in science is certainly not limited to the experimental or conceptual types associated with the work of individual, idealized scientists. The process of developing reliable knowledge also involves discourse. For example, mutual criticism among (non-idealized) scientists whose perspectives differ functions as an epistemic system of checks and balances. If one also considers the *demographic* dimension of knowledge, one finds important epistemic factors in re-instantiating knowledge in sites where it is relevant (Goldman 1999). (One may view this, alternatively, as distributing expert knowledge, whether to other scientists or to non-scientists.) Errors may also emerge in this discoursive process, where systems of credibility and the social institutions supporting discourse are directly relevant to the reliability of scientific knowledge.

For example, numerous sociological case studies have shown that scientists may exhibit prejudices based on gender, ethnicity, nationality, economic class, religion, ambition, and personal rivalries, etc. These cultural biases shape scientific inquiry (to use Rudwick's [1985] apt characterization of their indirect, but unmistakable causal role). Under some circumstances, they eclipse more trustworthy conclusions (while also giving illegitimate authority to biased positions). Viewing these errors cynically, one might dismiss all of science. From an error analytic perspective, however, the challenge is to characterize these errors clearly. Assuming that scientific knowledge is "socially constructed," we might learn how, ideally and pragmatically, to design and manage society to construct knowledge more effectively. As noted at the outset, we would hope to learn how not to repeat our past mistakes. In my typology, all the errors just noted fit into one category, reflecting (non-theoretical) cognitive biases. I do not intend to discount the diversity of influences that shape how scientists inevitably think. However, the mechanism of error, in my view, is similar in each case. That is, all these biases operate (causally) in a scientific community through the minds and actions of individual scientists (Allchin 1994). This implies, for example, that the errors resonate with theory-laden interpretations, noted above as an error type. One prospective countermeasure, then, is to deliberately ensure diverse perspectives within the discourse of a critically active scientific community, as suggested more systematically by Longino (1986) and Harding (1991). Many further strategies affecting the social structure of science might contribute further to coping with these errors. Their effectiveness, of course, will surely be contingent upon the particular culture. However, promoting trustworthy knowledge means, fundamentally, acknowledging cultural bias as an error type, which may or may not occur in any particular instance.

Another source of error, recently given considerable attention by scientists—and by the institutions that fund them—is fraud (National Academy of Science 1995, American Association for the Advancement of Science 2000). Fraud is also the type of error most popularly associated with "pathologies" of science. Many concerns often relate just to fiscal accountability (rather than the status of knowledge claims). Epistemically, however, fraud illustrates a failure in reliable communication among scientists. The transfer of observational conclusions and methods between scientists represents yet another layer of remapping. To build theories of broad scope or to perceive large scale or diffuse patterns, scientists often rely on each other's results. As nicely profiled by Shapin (1994), a scientific community depends on trust. Today, scientists measure trust through an informal system of credibility (Latour and Woolgar 1979; Hull 1988). A scientist's reputation based on past work and institutional status serves vicariously for gauging whether to trust a current report (Allchin 1998). The system rests on several assumptions, however, and any may fail. Once again, where the remapping of knowledge is faulty, error occurs. From an epistemic perspective of assembling reliable knowledge, mistaken credibility judgments (including fraud) form an identifiable error type.[5]

Transfer of relevant results may fail in other ways. First, scientists may not be aware of other relevant work if professional networks (including literature citation indices) are inadequate. Differences in language can be an obstacle. Results published in obscure journals, too, are easily overlooked. Correspondence networks may systematically exclude certain types of individuals. These form yet another error type: failures of communication.

Errors arising from the organization of knowledge among professional communities might well cap the global end of a spectrum of error types. However, one might also consider that many individuals and institutions hope to draw on scientific knowledge. Where their knowledge does not reflect available evidence (expressed, perhaps, in expert assessments), an error has occurred. Conservatively, one might consider this outside the domain of science proper. However, epistemic analysis is still relevant. The framework I have presented allows one to incorporate this as a simple extension of the remapping process on the local-derived scale. One may thus accommodate the *demographic* dimension of scientific knowledge (Goldman 1999). In this view, knowledge is inseparable from knowing agents.

5. In most cases of fraud, the error is detected long before its fraudulent nature.

It is not enough to say that something "is known" (passive voice). Rather, one must also specify who knows it, when, and where. One may characterize knowledge in terms of researchers, expert peers, scientists in neighboring fields, as well as citizens, educators, and officials making business or public policy decisions (in legislative, administrative, and judicial contexts). The scale of error types may thus easily include errors in "public understanding of science." For example, Toumey (1996) observes how American culture has cleaved the signs of scientific authority from actual scientific authority, allowing non-experts to "conjure" science in public forums. This enables error, as Toumey notes, from creationism to misconceptions about HIV transmission or fluoridation of water. Error types, here, would include: a breakdown in systems of expert testimony or certified authority, poor science journalism, and ineffective public education in nature of science. I characterize scientific knowledge demographically here to show how a typology of error easily accommodates issues about the "construction" of knowledge beyond narrow fields of expertise.

2.5. Second-order Errors

The analysis of errors above characterizes the epistemic process of forming and warranting scientific claims. A supplementary analysis might examine the institutional and cultural system that motivates and guides this behavior. Errors here range from managing labs and training technicians to educating new scientists, funding investigations and maintaining archives and communication networks. Such errors do not involve knowledge claims directly, but the knowledge-producing system. Does it produce knowledge effectively? Is error-remediation well administered? I call these second-order errors. Epistemic analysis here would focus on many features contingent upon the local culture.

Such errors are not insignificant. For example, feminists and other critics of science have profiled how *even knowledge that is perfectly reliable* (in the error-free sense) may nonetheless be severely misleading (e.g., Harding 1991). That is, the choice of topic or the framing of the question (the "problematic") may express a bias. One can misinterpret the results as representing the whole. At the very least, the scope of knowledge is not balanced. Hence, for example, research on primate social behavior or HIV infection might focus on males, obscuring significant differences in females. Or research on food production in nonindustrialized regions may focus on expensive fertilizers, irrigation and farm machinery, while ignoring whether husbandry, pest regulation, etc., might be equally effective as well as more culturally appropriate. These cases do not concern whether given scientific claims are reliable (my focus here), and hence do not fit in the classification above. Rather, these errors concern value choices about how to shape the scientific enterprise and its completeness. Remedying the science involves its social organization. (Note that "social" here includes social behavior in laboratories, just as the epistemic spectrum extends to the social level of discourse and culture.) I want simply to acknowledge these errors here and invite others to develop a fuller typology.

2.6. Relationships Among Types of Errors

One may certainly find important relationships among types of error. For example, local errors may be partly due to deeper, more global errors. Perceptions in the lab (observational) may be shaped unconsciously by theory preference (conceptual), which in turn may affected by cultural biases (discoursive). Or a lack of control (material) may be due to incomplete imagination regarding theoretical alternatives (conceptual). As a rule, I suggest, any relatively more global error provides a context allowing more local errors. Hence, solving the global problem should solve the local problem, but not the reverse. One way to interpret the local-global scale is through this asymmetry of error/resolution relationships.

My taxonomy of error does not introduce any novel type of error. Indeed, awareness of many error types already guides scientific practice. Recurring error types have resulted historically in informally institutionalized epistemic rules or heuristics. For this reason, I suspect, many philosophers hardly notice them. Analysis, however, serves two roles. First, philosophers and sociologists, drawing in part on good histories, can articulate the role of error and help describe, develop and justify strategies for minimizing known error types. Second, one can analyze the list of error types for completeness, enabling scientists to notice and avoid errors more systematically—a topic to which I now turn.

3. Resolving Anomalies and Probing for Error

A typology of error has significant potential for guiding error analysis and error probes. Consider, first, cases of anomalies or discordant results. When different results do not agree, or when observations contravene theory, an investigator is cued that something is wrong. An error has occurred. But where? Without further information, one cannot identify the error—that is, where to isolate it in the experimental-conceptual-cultural network. Further analysis of the discordance or anomaly is needed.

Darden (1991) has begun to structure this task specifically for conceptual change. She outlines possible ways theories may be at fault and thus revised (having assumed that experimental results are sound). Of course, no method is yet available for pinpointing a theoretical error immediately and unambiguously. But a catalog of possibilities can guide or enhance search. Under a more formal approach (such as in developing artificial intelligence or expert systems), such a list can aid a systematic scan of all possible errors (Darden and Lederberg 2000). In most cases, the strategies for anomaly resolution can prompt consideration of numerous possibilities or alert investigators to options otherwise overlooked. Darden's framework illustrates the potential of a broad typology of error. By using a spectrum of error types from experimental through discoursive scales, one can cast an analysis of error more widely and fully, without assuming that any given error is theoretical. One major role for a typology of error, then, is guiding analysis of anomalies or discordant results that signal the likely presence of error.

Not all errors announce themselves, however. Indeed, an error typically occurs or persists precisely when something wrong goes unnoticed or unaddressed. Sunderland (1992) emphasizes the pervasive cognitive tendency to prefer first solutions and to lower awareness or appreciation of exceptions and alternatives (also noted by Kuhn 1962). A countervailing strategy, then, is systematic review. Because error can masquerade as fact, neither agreement between observation and theory nor concordance of results can, by themselves, guarantee reliability. Deeper reliability depends on demonstrating that the conclusions are also free from error. This gap between ostensible verification and ultimate reliability is a basic principle of error analytics. "*Nothing's concluded until error's excluded,*" so the maxim goes. Accordingly, researchers need to actively consider, or *probe* for, error (Mayo 1996, pp. 4–7, 64, 184–85, 315, 445). This differs from Merton's "organized skepticism" and the skeptical attitude widely cited as a norm in science (e.g., American Association for the Advancement of Science 2000; National Academy of Science 1995; Rousseau 1992). Here, criticism must be justified and targeted explicitly to expose latent errors. Mere doubt does not suffice. One must *probe for specific errors.*

The concept of an error probe flirts with apparent paradox: how can one know or recognize precisely what one does not know or recognize? To escape this conundrum, one can deliberately scan the spectrum of possible errors. A major challenge, then, is to specify all such errors or error types. Some errors in each field may already be well documented and assembled in an informal *error repertoire:* all such errors must typically be checked. In these cases, one knows where to search for possible error. A complementary approach uses a typology of error. A taxonomy of error types can neither identify individual errors nor confirm them experimentally. But the error types can both organize a search for error and assist imaginative consideration of errors not yet encountered in the field. So, for example, even if one does not suspect gender bias, one can still apply a differently gendered perspective to review procedures, results, and interpretations. This would help reveal such error, if it exists. Explicitly assessing (or reassessing) purity of materials, appropriateness of statistical models, faithful reproduction of images, etc., can bolster conclusions. Ruling out error, or alternative explanations, now forms an important part of scientists' published arguments (Suppe 1998). A typology of error, as a major tool for probing error, contributes to the completeness of such arguments and the reliability of their conclusions.

Now, when does one probe for particular error types? Ideally one might consider error at every step. After all, remedying an error later will require additional time, expense, and resources. Unfortunately, checking for errors also involves time, expense, and resources. When, on balance, should one invest in "quality control"? I invite further analysis on a system of recommended "checkpoints." For example, the juncture of moving from a clear problem statement (or experimental aim) to experimental design seems one moment ripe for comprehensively reviewing potential error. The earlier one considers error, the more likely one can economize by ruling it out. In a similar way, preparing a manuscript for publication seems to motivate many researchers to anticipate criticisms of error from colleagues and to sharpen their focus. Is this checkpoint appropriately timed, or has the experimenter already passed the most opportune moments to catch most errors? What error types are especially pertinent at this stage? I suspect that there may be an "economy" of error probes. For example, extended reflection seems especially important just before large investments of time and resources. My informal appraisal is that, initially, standards of reliability are modest and that error probes become more severe, more common, and more formal as a research enterprise proceeds. I do not wish to propose here any comprehensive system of error review. Rather, I hope to highlight its importance and indicate the opportunities for addressing this issue more fully.

An ultimate strategy, of course, is to preempt repeated error by instituting appropriate safeguards wherever possible. A careful experimental design may address conditions known to introduce certain errors. Alternatively, one may plan to monitor experimental conditions for errors that one cannot prevent outright (e.g., supplemental controls, as mentioned above). Or one may collect information that will allow one to "correct for" otherwise unavoidable errors. Many such epistemic strategies are now standard in scientific practice. The local-derived spectrum of error types unifies these strategies into one conceptual framework, while underscoring their importance through the context of error analytics.

It remains an open challenge to develop norms or heuristics for anomaly resolution and error probes. For example, do certain error types occur more frequently and therefore deserve primary consideration? Checking for error generally requires additional effort or cost. Can knowledge of error types help scientists locate error more efficiently? In my experience, for instance, when researchers consider whether to test for a possible source of error, they weigh its prospective significance (or scope), their impression of its likelihood and the cost of checking for it. Glymour (1985) considered how multiple anomalies might help pinpoint a shared error. Can one generalize this strategy? What other such general strategies might draw on knowledge of error types? Again, I want to raise these issues here, without proposing any particular solution.

I will comment, however, on the resonance between different error types. Errors may be expressed in different ways simultaneously. Hence, a simple perceptual error (relatively local) may accompany a strong theoretical bias (more global), which in turn may reflect a cultural bias (more global still). Solving the local error will not necessarily solve the more global one, though solving the more global error should, ultimately, correct the local one. Accordingly, researchers should endeavor to identify and solve any error at its most global scale. Conceptualizing the structure of error along the local-global scale should help guide this task. Error analysis thus ideally includes searching for or imagining possible collateral errors (in other experimental contexts) that might reflect a global error. One might thereby discover a suite of disparate or undetected anomalies that reflect a deeper, unresolved problem (Kuhn 1962; Allchin 1992). Probing for collateral error may help researchers identify diffusely distributed, global errors more effectively. Another potential benefit of a typology of error, then, is helping to discover deeply entrenched, more global error.

4. Unifying Science Studies

The taxonomy of error proposed here (Figure 1) identifies in broad strokes elements that, minimally, must function properly—that is, *without* error—to ensure the production of reliable conclusions in science. It plainly includes both philosophical and sociological factors. Error in science does not discriminate between such academic categories. Error analytics, epitomized in this spectrum of error types, thus provides one framework for bridging domains of interpreting science often cast as mutually exclusive alternatives.

One hallmark of this framework is that one can acknowledge error in science without abandoning the goal of reliability. Sociologists, in particular, have earned a reputation for profiling error to "deconstruct" scientific authority and erode the status of scientific knowledge. Such studies have valuably exposed historical flaws in the scientific process. However, it is time now to try to remedy such flaws through new methods, whether at an experimental or discoursive level. Many philosophers, equally trenchant, refuse to acknowledge any factor outside idealized epistemological models. They generally have failed to consider, for example, the social mechanisms whereby epistemic norms are instantiated—or whether they meet practical demands of time, cost, and effort. While they respect observational data and evidence as foundational for good reasons, this alone fails to solve most cultural errors at the level of discourse. Philosophers, too, need to address how to "construct" reliable knowledge given problems of cultural context. Error analytics thus provides a meeting ground for sociologists and philosophers. It is neither wholly normative nor wholly descriptive. It also challenges everyone both to articulate or develop epistemic strategies that can realistically regulate each type of error.

Another hallmark of the framework of error types is showing how one can interpret fact and error in science according to the same concepts. That is, it takes seriously the Strong Programme's principle of symmetry (Bloor 1991, p. 7). But the solution, here, is not to adopt an exclusively sociological perspective. Rather, the typology of error embraces how philosophers and sociologists each describe certain errors, along with their complementary facts. Errors have many sources, some experimental, some conceptual, and some cultural. By symmetry, each parallel fact (that is free from the given error) relies on the very same experimental, conceptual, and cultural factors. Again, philosophical and sociological factors fit a common framework.

The spectrum of error types presented here only begins the challenge. Discourse among historians, anthropologists, literary analysts, psychologists, feminists, Marxists, etc., and from scientists and mathematicians as well, can all contribute to a fuller, more detailed taxonomy of error types. At the same time, they can also contribute to understanding how to circumvent or resolve such errors.

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