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ABSTRACT In many laboratory sciences, issues of cleanliness and purity are ever-present concerns. In materials science, keeping things (instruments, materials, people) clean structures the knowledge-making process. Using the work of Mary Douglas, I examine various contaminants, impurities and defects that are relevant to materials scientists. Importantly, though, definitions of what constitutes 'dirt' are multiple, overlapping and, often, formally contradictory; this means that impurities are as much positive resources as threatening pollutants. In materials science labs, where many kinds of actors and forms of life intersect, pollution may be used to rein in confusion and ambiguity. This paper traces various manifestations of laboratory dirt, then examines how (un)cleanliness enables certain moves in the materials science game.

Keywords clean, ethnography, laboratory, pollution

A Little Dirt Never Hurt Anyone:

Knowledge-Making and Contamination in Materials Science

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In the two decades since the genre emerged, studies of the social worlds of laboratories have often commented on practices such as abstraction, extraction, purification, filtering, rendering, and so forth – practices that bear the family resemblance that they deal with cleaning, cleansing and decontaminating bits of the world to make them more accessible to scientific study and to translate them into the workable material context of the lab.[1] A few analyses have even taken the theme of purification a step further, and have explored the ramifications of terms like 'clean' and 'sterile': among these, Pearl Katz has looked at the mechanisms of contamination and pollution avoidance in the operating room; Stacia Zabusky has described cleanliness concerns among engineers at the European Space Agency; and Barbara Rawlings and Stefan Hirschauer have both analysed the social organization and symbolic significance of sterility in, again, surgical settings.[2] In one particularly insightful article, Kathleen Jordan and Michael Lynch discuss contamination as they examine the various avatars of the plasmid prep in biology laboratories.[3] Jordan and Lynch's work is of interest because it uncovers the idiosyncrasies of local interpretations of the plasmid prep along with the forces and entities which can contaminate it and make it succeed or fail; this sort of flexibility in

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discerning contaminants and ways of getting rid of them is a recurrent theme in understanding dirt and cleanliness in laboratories.

What these and a host of other studies show is that dirt and pollution are driving forces in the social life of a wide range of sciences; nevertheless, a detailed examination of the rôle of dirt in laboratory settings, containing an outline of the various kinds of pollution, the ways in which they are dealt with and/or used as resources, and their intertwining with the social organization of laboratory participants, is still lacking. One particularly important lacuna is what might be called the 'knowledge element'. Those analyses most focused on purity and cleanliness, such as those by Hirschauer, Katz, Rawlings and Zabusky, concern the pragmatic rôle of contamination (and the social forms attendant upon it) in the achievement of desired outcomes (in surgery or engineering), rather than showing how these practical considerations, along with the dirt embedded in them, go into the production of knowledge.

This is all the more surprising given that one of the foremost contributors to the field of science studies, Mary Douglas, is also the foremost contributor to traditional anthropology's understanding of pollution and its rôle in the creation of socially held knowledge about the world. Many science studies scholars, such as David Bloor, Barry Barnes, Steven Shapin, Michiel Schwarz and Michael Thompson, have capitalized on her later works – *Natural Symbols* (1970), *Implicit Meanings* (1975), *How Institutions Think* (1986) and studies of *Risk*[4] – to unpack the cosmologies and hierarchies of social groups that produce scientific knowledge.[5] Her early explication of dirt, *Purity and Danger* (1966),[6] however, has largely been neglected in science studies, despite the implications it might have for analysing the production of knowledge and culture in the laboratory.

This paper does not aspire to a totalizing, cross-disciplinary analysis of cleanliness and dirt that would do for laboratory studies what *Purity and Danger* did for anthropology and comparative religion. Indeed, I will try not to take a synoptic view of practices like purifying, etching, polishing, annealing, milling, coating, and so forth. There is no one thing uniting these and other disparate laboratory phenomena: rather, they are overlapping strands making up an analytically interesting thread around themes of purity, cleanliness and contamination. I leave the exact boundaries of this thread to emerge throughout my paper, but its endpoints are generally the practices and techniques of ridding, cleansing and purifying parts of the laboratory world, as well as the entities and phenomena that are thereby cleansed or avoided. I extend my analysis, however, to follow the variabilities of lab practice, where what is labelled as polluting one minute is turned into a necessary tool the next, and where the 'clean' and 'dirty' parts of the world are often overlapping and intermingled.

This study therefore moves somewhat beyond Douglas' framework (at least in *Purity and Danger*), where 'the central idea is that accusations of causing dirt and defilement are weapons against disorderly behaviour'.[7] Dirt as a means to control behaviour is a critical fact in many laboratory sciences; but I hope to show that pollution and contamination are often sought out by scientists as ways to expand the boundaries of their knowledge, as solutions to problems and anomalies, and as guides in their local logic of practice. Nevertheless, the threatening aspects of pollution are rarely far from the surface, in ways that make Douglas' ideas essential starting points in talking about laboratory dirt.

What is Materials Science?

The first such point is that pollution emerges within communities. Douglas explains that virtually all social groups have ideas about dirt and defilement, but that the meanings attributed to contamination can only be understood in relation to local contexts, meanings and practices. Thus it seems clear that practically every laboratory and field science has vocabularies of pollution and purification, contamination and cleansing.[8] While we might be tempted to say something about the rôle of dirt across all these vocabularies, the empirical data needed for such a comparison have not yet been collected. Moreover, even within a particular scientific setting, ideas about dirt can be highly variable. For the moment it is necessary to take a fine-grained look at a few interrelated and interwoven laboratory contexts and to examine the specificities of how dirt is (often literally) embedded in those settings.

The particular setting for this dirt story, therefore, is a small group of graduate students working under one professor in the Materials Science and Engineering Department at Cornell University. I carried out my observations continuously over the summers of 1998 and 1999, and intermittently between-times (summers happened to be the periods of most active research for my informants as well). Four graduate students were members of the group during the time of my ethnography: I will refer to them as Henry, Rudy, Angus and Paul.[9] They constituted my pool of key informants, but I also observed and talked with their group leader (Professor Sitman), several of their undergraduate laboratory assistants, and the many other technicians, professors, graduate students and laboratory personnel with whom they interacted. In addition, as I became more and more interested in how my informants dealt with cleanliness, I decided to observe the hazardous waste inspectors of the Cornell Environmental Health and Safety Office, one of the campus entities charged with regulating certain important kinds of pollution.

There are a number of reasons why materials science is an exemplary site for looking at issues of cleanliness and dirt in the lab. 'Materials science' is an umbrella term for an extraordinarily diverse set of practices and occupational and disciplinary affiliations. It includes, but is certainly not limited to, the study of metals, polymers, ceramics, glasses and composites, with respect to their electrical, mechanical, thermal, optical, and other properties. We know from Mary Douglas that purity and danger become most relevant at the boundaries between cultures and systems of classification. Laboratory settings where different kinds of knowledge interact are places where dirt and defilement are likely to matter.

The institutional arrangements for materials science at Cornell highlight this heterogeneity. My informants belong to the Materials *Science* and *Engineering* Department, a field within Cornell's School of Engineering. They also have a close relationship with the Cornell Center for Materials Research [CCMR], however, which is supervised largely by physics faculty located within the College of Arts and Sciences; moreover, CCMR has facilities in physics, engineering, geology and chemistry buildings, all of which were utilized by my informants during my ethnography. Cornell's interest in materials science has been intense since 1959, when it was awarded funds for an ARPA Interdisciplinary Laboratory (IDL) in that area.[10]

Many who receive the appellation 'materials scientist' might alternately refer to themselves as 'scientists', 'engineers', or as practitioners of more academically traditional disciplines (chemists, physicists, applied physicists, geologists). Alternatively, they may present themselves in terms of the material or application with which they work (ceramists, metallurgists, 'device' people, 'plastics' people). One important aspect of materials science is its relation and orientation to other engineering sciences – materials science is about both making and understanding, and many of its products (both intellectual and material) are embedded in numerous high- and low-tech artefacts.[11] From this perspective, we can see materials science as encompassing (1) the characterization of the properties of materials; (2) the investigation of how those properties come to be; (3) research into how to manipulate such characteristics in individual specimens; and (4) the production, on industrial scales and using industrial methods, of those same characteristics in materials which go on to form components of devices in widespread application.

With this understanding of materials science, a second reason for the relevance of dirt emerges; for the distinction between dirt and non-dirt is tied closely to ideas about the organization of matter. Douglas' initial definition of dirt, for instance, is that it is 'matter out of place'. As she puts it, this definition . . .

> . . . is a very suggestive approach. It implies two conditions: a set of ordered relations and a contravention of that order. Dirt then, is never a unique, isolated event. Where there is dirt there is system. Dirt is the by-product of systematic ordering and classification of matter, in so far as ordering involves rejecting inappropriate elements. This idea of dirt takes us straight into the field of symbolism and promises a link-up with more obviously symbolic systems of purity.[12]

Materials science, insofar as it *is* the 'systematic ordering and classification of matter' should, by Douglas' logic, have a close relationship with notions of purity. In general, contamination can pose a serious danger to the practice of materials science; the possibility of *dis*order, however introduced, threatens to reverse all of the materials scientist's work in bringing about *order*.

In fact, at first glance it might appear that dirt is always the materials scientist's enemy; as we shall see, though, this belief misses many of the subtleties about cleanliness that are key to the practice of the discipline. In certain areas of materials science, particularly those most closely associated with electrical engineering and the semiconductor industry, the rhetoric of cleanliness is employed freely, and entangled in arguments for nanotechnology and miniaturization that verge on technological determinism.[13] Note, for example, this quote from the website of Intel (a company that uses bunnysuited clean-room technicians as icons and selling points for its line of microelectronics products):

> Even though the basic material for a microprocessor is sand, a single speck of dust in the air of a fab could ruin thousands of chips. So the environment in which microprocessors are manufactured has to be very clean. In fact the clean rooms in a fab where the chips are made is more than ten thousand times cleaner than a hospital operating theatre. A 'class one' clean room, the cleanest of clean rooms, has one speck of dust per square foot. . . . It's hard to imagine the absolute cleanliness of a fab. However hard you try to think how clean a fab is, it's cleaner.[14]

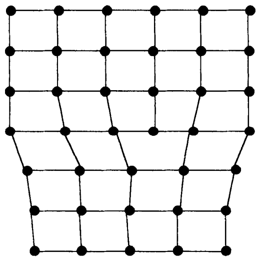
One last reason to look at dirt and defilement in materials science, then, is to examine more carefully some of the most public talk about cleanliness in materials science. One purpose of this paper is to show that the systematic expulsion of contamination found in clean rooms can only be understood as part of a wider field of materials science and engineering, where 'unclean' laboratory practices are often prerequisites for the work done in fabs.

What Counts as Dirt?

In taking dirt as matter out of place, it becomes important to know what materials scientists take to be matter *in* place. Since the graduate students in Professor Sitman's lab deal primarily with metals and ceramics, I take those subdisciplines as my starting point, noting, however, that similar observations could be reproduced for other areas. The question, then, is what it takes for a metal or ceramic to be 'clean', for its matter to be 'in place'. Cleanliness is, as we shall see, a matter both of degree and of context, but, for certain tasks, metallurgists and ceramicists do produce idealizations of their materials that visualize a perfect state of cleanliness.

Most calculations, for instance, begin by assuming that a material is a 'perfect crystal' – that is to say, one in which all of its atoms are of the type indicated by the material's chemical formula, in their proper proportion and arranged with absolute order. Such calculations are not usually performed with a physically present specimen of the material in mind, however; on the other hand, even materials which are known not to be perfect crystals are often referred to by the orientation of their 'unit cell', a system of reference which pictures the material as essentially consisting of repetitions of the same arrangements of the same kinds of atoms. A shorthand way of describing 'gold', for instance, might be to say that it is '[1,1,0]' (a kind of unit cell), even though the speaker recognizes that the

FIGURE 1
Dislocation



material in question is neither purely made up of gold atoms, nor purely made up of [1,1,0] cells.

In the perfect crystal, then, or even in the material as pictured by the shorthand of its unit cell, matter is, from a certain perspective, perfectly in place. 'Defects', when they occur, are occurrences of disorder, or matter straying from its place, with respect to the exemplary arrangement. Figure 1, for instance, shows a kind of defect called a 'dislocation', in which the perfect crystal is perturbed at a point by an atom which doesn't connect properly with its neighbours (in practice, there are several types of dislocations, and they interact with their surroundings in somewhat more complicated ways, but Figure 1 is similar to representations of dislocations in introductory materials-science textbooks). Dislocations figure as matter out of place – they are obvious distortions of the perfect crystal. As such, they *can* figure as dirt – as unnecessary, even harmful, contaminants to a material, and so, on occasion, materials scientists will be careful to minimize their presence. Dislocations can, for instance, severely degrade certain electrical properties of materials; hence, a materials scientist trying to engineer just those properties will treat dislocations as a kind of pollution, a phenomenon to be avoided or expunged.

Other properties, however, particularly mechanical ones such as yield strength, may be significantly enhanced by the *presence* of dislocations. Thus, for applications where such properties are important, it may be necessary to induce dislocations within the material. Indeed, materials scientists have a number of techniques for doing just that. Importantly, though, dislocations *qua* dirt and dislocations *qua* desired entities do not exist independently of each other – for many applications, both the electrical characteristics that they degrade and the mechanical ones that they enhance may be desired. A representative quotation from the NSF Panel on Atomic Resolution Microscopy shows both the primacy of the perfect crystal as a 'clean' form, as well as the occasional desirability of some defects:

> For example, when the regularity of a crystal breaks down, the resulting defects determine many important properties of materials systems. Indeed, these deviations from the perfect crystal are often necessary in materials used to fabricate useful devices of all kinds. Understanding and

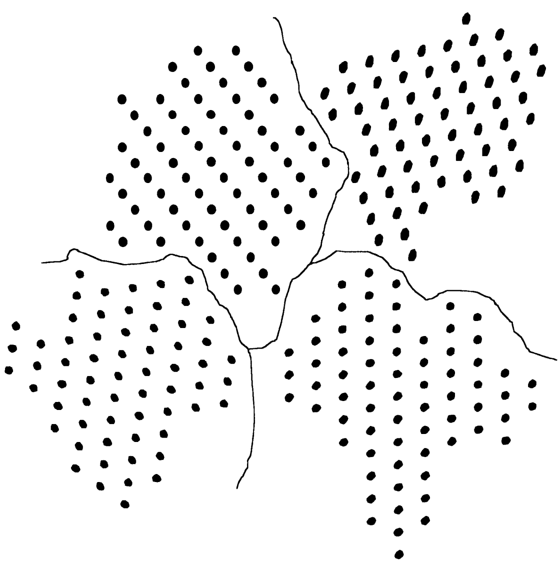
> control of these features are critical for extending the limits of advanced materials technology.[15]

The materials scientist must, therefore, evaluate both the 'dirty' and 'clean' valences of dislocations and other defects, and satisfy competing constraints to accomplish the task of creating a material that performs in the hoped-for way.

There are many crystalline defects besides dislocations (twins, inclusions, decorations, voids, to name a few) but one more will summarize my point. 'Grain boundaries' occur when a crystalline material begins to solidify in several places at once, resulting in heterogeneous orientations of its atoms. Again, grain boundaries interrupt the form of the perfect crystal, and as such can figure as contaminants (see Figure 2). For some applications, grain boundaries are utterly anathema, and great lengths may be gone to in order to avoid them. For example, an entire industry has been built around growing high-performance jet- and rocket-engine turbine blades from very large single crystals of nickel-base superalloys because of the dangers grain boundaries can pose to mechanical integrity in high-temperature, high-stress conditions.

On other occasions, for other tasks, however, polycrystallinity may be entirely in order. Grain boundaries have the property, for instance, of blocking the movement of matter within a material; hence, they interact in various ways with other defects, many of which can figure as kinds of contaminants in their own right. One trick for enhancing yield strength, for instance, is to increase the number of grain boundaries, thereby blocking the movement of dislocations, and causing them to pile up within the

FIGURE 2
Grain Boundaries



material. Thus grain boundaries, though always labelled as ‘defects’, may at times not figure as contaminating nuisances, since they may constitute entirely the right kind of matter in place. The complexities of dirt continue to ramify, however; even when grain boundaries may be treated as matter in place, they can act as attractors for impurities known as ‘decorations’ which may be decidedly matter *out* of place. Again, the materials scientist, in engineering the properties of materials for applications, must navigate between the various valences of material phenomena (‘dirt’, ‘defect’, ‘decoration’ *vs* ‘desired property’) to achieve the sought-for outcome.

Other Modes of Pollution

Crystalline defects are, of course, only one kind of potential pollution with which materials scientists must deal. The world of materials science is filled with entities and phenomena that threaten (or promise) to induce pollution and contamination, to push matter out of place, to turn ordered material into dirt. Some of these modes of pollution are continuous with those experienced in ostensibly non-technical forms of life. Contact between a clean material and the dirty world, for instance, can transmit pollution in both technical and non-technical contexts.[16]

In the materials science case, the rationale for worrying about such exposure (not just to physical touch but also to heat, magnetism, light and other radiation, as well as noise and other vibrations) is that it may destroy desirable features or introduce undesirable ones, cause contamination, or bring about some physical or chemical change in the material’s form. Obviously, though, some kinds of contact are not treated as polluting – the materials scientist must be able to effect some physical communication between world and specimen to change its form in desired ways or to integrate it into applications. Thus the material must be both susceptible to the manipulations of ‘clean’ contact and resistant to the contaminating influence of ‘dirty’ contact. That is, contact can push matter into or out of place, depending on context. The material must be engineered so that it ‘knows’ which is which. Working through this sort of engineering is one of the materials scientist’s most difficult tasks. As always, the line between ‘cleaning’ and ‘dirtying’ is a tenuous one.

Along with contact pollution are the various ways in which unknown or undesirable entities (ions, atoms, molecules, aggregates, and the like) can adhere or inhere to a material; these are essentially like weeds in the materials scientist’s garden, and they arrive on and in materials in much they same way as weeds in a backyard plot. Sometimes these contaminants are introduced by the actions of scientists themselves: they may mix in the wrong chemical or not adequately protect a specimen from ambient water vapour or fail to clear away dust and other macroscopic debris. For instance, Rudy at one point applied blue nail polish to the sides of a specimen as a sealant. On the sides of the specimen, therefore, the polish was, for the moment, not treated as a contaminant. Unfortunately for Rudy, flecks of polish began turning up on the top face of the specimen, which was meant to be clean. These flecks, like many kinds of surface dirt, interfered with further experimentation by obscuring or destroying the nanoscale features Rudy was trying to create.

At other times, the presence of dirt may be intricately bound up with how materials scientists categorize and recategorize objects in the world, depending upon how those objects are currently relevant. The way in which my informants usually obtained their materials, for instance, was to order them from suppliers by spec. Materials scientists have a whole jargon centred around such specifications, many of them having to do with levels of purity: a cylinder filled with one gas may be labelled as having a certain ppb (parts per billion) of other gases present, or a batch of metal may be said to be '4-9' (that is, 99.9999% pure). Is '4-9 platinum' clean platinum or dirty? Under most conditions it is very clean platinum indeed, despite the advertisement of impurity in its name. Such impurity surfaces, though, when the contaminant becomes relevant for the task at hand. For example, Angus, for his first two years in the lab group, worked with 5-9 platinum on a project involving surface reactions; at the end of his second year, however, he discovered that many of the effects he was seeing were due to the presence of minute traces of boron in the platinum. The platinum had been 'clean' while the few contaminants it contained were thought to be irrelevant; with a new understanding of the rôle of boron in the reaction, however, came a recategorization of the platinum as contaminated in a relevant way.

This points up two further operators of pollution, namely time and space. On the one hand, time can create dirt in the sense that materials scientists are constantly having to reconfront their categorizations of the world, and what was seen as clean one day may not be the next (although the dirt that is subsequently real-ized is usually seen, as in the example of Angus' platinum, as having been there all along). In other cases, time is taken to have been what enabled the creation of disorder out of order. Materials such as silicon, for instance, will simply lapse into a dirty state if left unattended and unprotected (silicon does so quite quickly because it is prone to form an oxide layer – again, though, the oxide is only a relevant impurity under certain conditions).

Space and time can combine to enable dirt in the sense that where and with whom a material has been, and what has been done to it in the past, all contribute to its possible contamination. At one level, some materials (coal and marble being well-known examples) vary in their properties depending upon where they are mined out of the earth, even though they are still referred to by the same name. In more complicated ways the history of a particular sample of a material may be important in evaluating what kind of, and how many, contaminants it may contain. For example, the platinum in Angus' experiment contained boron because it was re-cycled from platinum used in glass manufacturing; boron, as well as silicon, iron, calcium, and a few other elements are also used in making glass, and so traces of those elements found their way into his specimens. Platinum from some other source, though still '5–9' and hence 'impure' by definition, might have contained different, non-interfering and hence non-contaminating, kinds of impurities.

All the modes of pollution I have just outlined pervade the materials scientist's life. Nevertheless, some (contact with or exposure to a contaminating world, induced recategorization, and the vagaries of time and space) are less specific to materials science contexts than others (such as the crystalline defects I described earlier). As such, these less specifically materials-scientific forms of pollution are subject to what might be called 'common laboratory sense' – a general attunement to those kinds of pollution common to many laboratory sciences, an attunement which can be transported between different kinds of laboratories and disciplines, even if it must be somewhat modified to fit new contexts. Environmental Health and Safety (EH&S) officers, for instance, run common training sessions to educate all different kinds of laboratory workers about the various dangers and environmental hazards they may face. Nevertheless, they are acutely conscious that different labs can contain quite different kinds of pollution, and mandate that each lab group devise a 'chemical hygiene plan' to adapt common sense to the particular contaminants they may face.

Several things make crystalline defects distinct as forms of pollution within materials science from more universal kinds of laboratory contamination. Defects are more exclusively worked into the specific knowledge of materials science. Just as (from Barbara Rawlings' study of operating rooms) almost anyone can tell the difference between a 'bloody' knife and a 'clean' one, but only certain people can tell the difference between a 'clean' knife and a 'sterile' one, in a laboratory setting almost anyone can tell the difference between, say, a 'dirty' gold film and a 'clean' one, but only certain people (practitioners of materials science and related disciplines) can tell the difference between 3-9 and 4-9 platinum, or a polycrystalline gold film and a single-crystal one.

Similarly, ordinary kinds of dirt (dust, hair, blood, oil, and the like) are usually less ambiguously polluting than defects and other contaminants specific to materials science. Materials scientists know a great deal about the chemistry of decorations, the surface science of oxides, and the physics of dislocations, and very little about the biology of hair or the organic chemistry of oil. Thus they more quickly dismiss the latter as contaminants, while reserving judgement in most instances as to whether the former are kinds of dirt (which should be cleansed or avoided) or objects of study (which should be investigated and characterized).

Importantly, it is part of what constitutes materials science to know how to produce twins, dislocations, grain boundaries and other defects by means of heating, rolling, pressing, etching, and otherwise 'treating' (in a technical sense) materials. Materials scientists spend a great deal of their time figuring out exactly how to fine-tune their procedures so as to control the appearance of defect dirt; even if a procedure inadvertently produces an overabundance of an undesired defect, the experimenter has still learned something valuable – on some other occasion, that kind of defect may become desirable, and the same procedure can be used to produce it on demand.

These examples illustrate a fundamental point: that 'dirt' is always relative, although some dirt is more relative than others; a biochemist and a materials scientist would probably disagree about whether a grain boundary is a relevant contaminant, but they are more likely to concur that mud or nail clippings are polluting. Still, we have to remember the variability in meanings of dirt. For instance, nail polish used as a sealant to protect a salt substrate from water during etching is potentially contaminating, but perceived as a necessary tool, whereas nail polish *qua* nail polish (say, spilt while applying it to one's toes) is a kind of 'ordinary' dirt.

The difference is that nail polish *qua* sealant is 'materials science' dirt, the nature of which is subject to the theories and characterization techniques of the discipline, whereas in its more mundane uses nail polish is simply dirt to be warded off or cleansed away (likewise, mud *qua* site for microbial growth might be a kind of 'biochemical dirt', whereas the same mud, in the same biochemistry laboratory, but now tracked in on somebody's shoes, would be a kind of 'ordinary' dirt).[17] In Mary Douglas' words:

> [W]hat is clean in relation to one thing may be unclean in relation to another, and vice versa. The idiom of pollution lends itself to a complex algebra which takes into account the variables in each context.[18]

Ordinary dirt lends itself to a somewhat less complex algebra than those kinds of dirt specific to the science in question – still, significant boundary-work goes into deciding what can be relegated to 'ordinary dirt' for any given science.[19]

Pollution Ritual

Lastly, before I begin to describe some of the social and epistemological consequences of pollution, let me enumerate some of the practical means by which dirt is avoided and/or removed. 'Pollution ritual' is Douglas' term for such practices, and it is the terminology I will adopt here; as she says, she intends the notion of ritual to be operative wherever we examine culture, rather than limited to 'primitive' cultures or religious rites. Nevertheless, there may be objections to my use of this terminology to describe lab practices, to which I will respond in the next sections. For the moment, though, it will suffice to remember that, for Douglas, rituals of cleanliness, rather than being merely rational reactions to the reality of dirt, are bound together with our knowledge of how to describe the world and how to put its components into their categorical pigeonholes; that is to say:

> [W]hen we honestly reflect on our busy scrubbings and cleanings in this light we know that we are not mainly trying to avoid disease. We are separating, placing boundaries, making visible statements about the home that we are intending to create out of the material house.[20]

This statement requires little modification to fit the world of materials science.

Some pollution rituals are utter second nature to materials scientists. Practices such as carrying specimens in a sample case (usually a small plastic dish with a twist-on cap); picking specimens up with tweezers; scouting them for dust, hair and other macroscopic debris; and keeping them in vessels filled with moisture-absorbing vermiculite, are all usually unmarked actions.[21] Exceptions to such rules, such as picking a specimen up with one's fingers, are usually explicitly motivated and carried out with a higher degree of attention and concentration. Like Pearl Katz, I found that levels of concentration were generally highest when materials were being cleaned, or when they were transitioning into 'clean' environments; for example, while using any type of microscope my informants were often jovial and high-spirited *except* when moving specimens into or out of the microscope itself, when cleanliness issues were deemed to be most pressing, even though, at other times (as I will talk about later), they could easily orient themselves to the constant presence of pollution *inside* the microscope.

Other rituals are less taken-for-granted. Some, like specific combinations of chemicals for an acid bath, or specific procedures for etching, can be quite elaborate and continually variable; in this they somewhat resemble the immunoassay 'translucent boxes' described by Kathleen Jordan and Michael Lynch.[22] Lab workers may not know or care exactly how such techniques work, and different labs often have their own particular 'recipes' for such rituals (where knowledge about such techniques passes more or less freely between labs that are in contact with each other).[23] Learning how and when to pick up such knowledge is an important part of the training of materials scientists. Indeed, learning ways of keeping materials clean is a vital component of a materials scientist's knowledge; but, as we shall see, so is knowledge of when it is necessary *not* to keep things clean.

Finally, it is important to keep in mind that the act of cleaning can pose a threat to the materials scientist's aims in understanding and manipulating the organization of matter. Cleaning rituals may be blunt instruments, removing as many of a material's positive properties as negative ones. By going after dirt, experimenters may destroy just those effects for which they were looking; or, particularly when sample sizes are small, they may destroy the entire material itself. Thus, materials scientists almost always have to adjust their standards of cleanliness by dint of the cleaning options that are available to them; for they know that anything they do to remove pollution is likely to be tedious and/or uncertain and/or counterproductive.

Sometimes the act of cleaning is a kind of journey through dirt and back again. Polishing a layer of oxide off of a 'silicon on insulator' (SOI) wafer, for instance, involves covering the wafer with (decidedly dirty) oil, then grinding the oxide off with progressively finer diamond-coated grinding pads. With each pad, thinner and thinner slices of oxide come off, so that the wafer is, in a sense, constantly getting cleaner, but it is only 'clean' when the process is done and the oil can be washed off. Note that this is a case where there is theoretically a clear point where the specimen can be 'too clean' – the objective is to grind right down to where the oxide leaves off and no more, since the film underneath is quite thin. Note, too, that this becomes considerably more complex in practice, since a hysteresis develops as this point is approached; the thinner the layer of oxide, the more the benefits of grinding it off are balanced by the drawbacks of letting bits of diamond and ground-off oxide contaminate the wafer. Learning when to stop polishing was, like many other aspects of cleanliness, an integral part of the process of acquiring the tacit knowledge of materials science for my informants. That is, pollution ritual is often a difficult thing to learn how to do properly; this seems to be a point of departure from Douglas' framework, which includes little room for problems in learning how to perform pollution rituals, and even less for interpretive flexibility in determining whether they have been performed correctly.

Objections and Responses

At this point, I want to raise two standard objections to the sort of analysis I am presenting, firstly to acknowledge that this framework is not without its detractors, and secondly to advance my argument by presenting some responses to criticism. The first argument is one long familiar both to practitioners of science studies and to followers of Mary Douglas: namely, the realist objection to social analyses of theories of the physical world. It runs something like this:

> You have shown that materials scientists are worried about cleanliness. And you have shown that polluting phenomena may also be beneficial. But why should this be of interest? Surely scientists are only worried about the cleanliness of their materials because contamination of those materials really would upset their results?

This is the type of argument that Douglas labels 'medical materialism'. It assumes, in general, that rules of hygiene are what they are because they protect us from various maladies and are hence grounded in proper medical reasoning, rather than in the symbolism of social structure. She combats this type of thinking by arguing that all pollution rules *can* be rationalized as a product of 'proper' hygiene, but no such rule can be completely abstracted from its symbolic element; that is, 'our idea of dirt is compounded of two things, care for hygiene and respect for conventions. The rules of hygiene change, of course, with changes in our state of knowledge', but conventions, for her, are the product of how a society is organized, how open it is and how hierarchically its members are situated.[24] Like Dan Jorgensen and others, however, I find Douglas' straightforward linking of pollution rules and classificatory categories to social structure unconvincing; as Jorgensen says, with respect to the echidna and the kuyaam, 'in the end, *pace* Douglas, differences in the treatment of anomalous animals are not readily reducible to variations in social structure'.[25] Pollution rules do seem to have an irreducibly social kernel, however, in that such rules are constituted by, and constitutive of, cultural life. But why divide the rules that govern cleanliness into 'symbolic' *versus* 'hygienic', 'knowledge-based' components? I have already tried to show that materials science knowledge (of, for example, crystalline defects) is inextricable from rules about what makes a material clean or unclean in a given situation for a given purpose; as we shall see later, 'dirt' and the conventions that relate to it can also be positive, sought-for resources in the construction of new domains of materials science knowledge.

The other well-known argument against analyses of this type has no particular label, but might be called the 'Winchian critique'. This is the argument rehearsed by Harry Collins in his debate with Stefan Hirschauer in *Social Studies of Science* concerning Hirschauer's analysis of the symbolic significance of surgical 'rituals' in the operating room.[26] The gist of this critique is that it is a category violation to speak of 'ritual' and 'symbol' in a technical domain where such considerations simply don't enter (that is, in the terminology of Ludwig Wittgenstein and Peter Winch, on whom Collins draws, 'ritual' and 'symbol' are simply not terms in the 'language game' which constitutes the surgical form of life). My own analysis would be prey to this critique in the sense that I, too, am using terms from outside my informants' narrowly technical form of life. Materials scientists do not often speak of 'dirt' *per se*, and certainly not in the sense of 'matter out of place', nor do they usually refer to their practices as 'pollution rituals'.

The Winchian does, therefore, have a good point. One reason my informants did not speak about 'dirt' was that, as I have shown, virtually all of the entities I have described as having the potential to pollute or contaminate also have the potential to enhance the properties of a material; as Collins and Winch would probably be the first to point out, both 'dirt', and the phenomena which can constitute it, are indexical, and have to be evaluated in context. The fact of dirt is too variable to be pinned down as having any unchanging essence; instead, materials scientists speak of 'dislocations' or 'grain boundaries', and keep track, from context to context, of whether that particular entity is a form of dirt at a given moment.

Nevertheless, though the relativist critique is challenging, it is hardly a knock-down blow. Indeed, by answering it we may gain new insights into how dirt works. First, my informants all find it easy to attune to the similarities between the phenomena I have described; they recognize that there is something uniting practices like polishing, etching, dusting, annealing, and other 'pollution rituals', and that there is also something uniting the entities which are being cleansed by such rituals, whether they are dislocations and grain boundaries or hair and condensation. Practically all materials scientists with whom I have spoken readily acknowledge the rôle of considerations of purity and cleanliness in their work; though they might be suspicious at first of an analyst's category like 'dirt', it takes relatively little to orient them to the considerations I have been describing.

Such informant agreement is valuable, of course, but also notoriously ambiguous. A somewhat more interesting observation is that many of the actors in the materials science form of life themselves commit, as a practical matter, what might be called 'quasi-category violations'. That is, some of the individuals embedded in this language game habitually make ordinary objects and practices seem strange and exotic in much the same way I do as an ethnographer. This is particularly true of actors whose job it is to enforce standards of cleanliness. For example, operators of clean rooms have large manuals outlining how people in the clean room should accomplish such mundane tasks as pouring a bottle of water; the action of pouring might seem to be the same as outside the clean room, but operators need to impress on users of the clean room the necessity for care, diligence and vigilance (all terms, as Katz and Zabusky point out, associated with orientation to cleanliness).

Likewise, Environmental Health and Safety officers intrude on the lab to relabel the world according to their own scheme, a scheme often antithetical to that of materials scientists. Here is a clear example of the language game of materials science coming into contact with other forms of life that profoundly influence the shape of materials science knowledge. Bureaucratic entities such as the Occupational Safety and Health Administration (OSHA), the Environmental Protection Agency (EPA), and Cornell's Office of Environmental Health and Safety (EH&S) know well that idiosyncratic (local) standards of cleanliness and practices of pollution avoidance abound, but they make it their duty to impose a universal (or at least national) standard by which they can compare laboratories around the country and identify ones whose standards have become *too* idiosyncratic. These hazardous waste officers try to construct uniform practice in a number of ways. They train and inform laboratory workers, disciplining not just their practice, but their whole bodily habitus, with regard to dangerous chemicals and equipment: this includes (a) what to wear – not just lab coats and safety glasses, but page after page of guidelines on which *kinds* of gloves to wear when using which kinds of chemicals; (b) how to move – how to stand next to a fume hood, how to scrape a label off a bottle, how to carry a gas cylinder; and (c) how to organize the world – what chemicals can be stored together, what materials can be used for storage, how to label new chemicals and old waste.[27]

When labs are inspected, much of the inspector's job revolves around systematic violation of the laboratory's way of seeing the world. For instance, EPA inspectors have the prerogative to point to some assemblage of chemicals and equipment and deem it 'inherently waste-like' – and, *ipso facto*, that assemblage becomes waste, with all the civil dangers to the lab that accompany the presence of waste – fines, possible closure of the lab, forced changes in practice and equipment. But the laboratory workers, and even the EPA inspectors themselves, may know that something labelled as 'inherently waste-like' may not be waste in the local world of laboratory life; it may, for instance, be a slightly messy acid bath placed in the wrong part of the lab, or a bottle of old and improperly labelled, but still useful, chemicals located near a row of waste bottles.

That is, the inherence of the waste is only relative to the universal guidelines of safety and cleanliness laid down by EPA, and the term 'inherently waste-like' is only deployed to insure adherence to those guidelines. Like sexuality, criminality, insanity and work, cleanliness is a kind of Foucauldian discourse allowing for surveillance and discipline. The laboratory, as Michael Lynch has pointed out, is a place where objects of knowledge and knowing subjects are both placed under scrutiny.[28] For example, EH&S requires waste bottles to be labelled with contents, date, and the name of the preparer, so that both the waste, and the person responsible for it, are in a sense held together discursively. The discourses of cleanliness are also inscribed on the bodies of laboratory workers. People are sources of dirt, not merely in their actions but also in the constant sloughing off of bodily detritus such as hair, skin and sweat, and a great deal of work goes into training laboratory workers to move and act so as to channel this dirt effectively. As the users' manual for the clean room at Cornell puts it:

> You are the biggest source of contamination in the clean room. Your clothes, your feet, your skin, and your hair are filthy, on an absolute scale. We must each take considerable personal care to assure that the clean room remains clean, for everyone's benefit.[29]

People can also be sinks for contamination, thereby allowing for further surveillance. When laboratory accidents involving hazardous chemicals occur, for example, EH&S requires the people involved to get immediate medical examinations. The records of the examinations are then kept for 30 years in case unknown long-term effects of the chemicals begin to show up.

I will not pursue this sort of Foucauldian analysis of cleanliness here (although I think much remains to be done), but I would point out that Foucault's attention to power and discourse provides yet another answer to the Winchian critique. Though the terms and practices I am describing may have very specific technical meanings in the forms of life of a materials science laboratory, they may also be part of a more general discourse which governs and unites both large and powerful organizations such as the EPA and small-scale, mundane actions like using a pair of tweezers to move a specimen, as well as a great deal in between.

Interestingly, this uniting of different worlds through discipline and surveillance is also the point at which Mary Douglas provides her own answer to the Winchians. That is, OSHA, EPA and EH&S look very much like the societies Douglas describes which consider the outside world evil and polluting, and hence possess highly developed systems of categorization and taboo. For Douglas, 'dirt' is a concept which, when considered anthropologically, may seem foreign to the actors precisely because it is a concept which becomes most important at the boundaries between language games, at the points where forms of life rub up against each other, often uncomfortably. Thus, while the relativist critique retains its validity, its insistence that analysts stay true to the actors' language game blocks any attempt to understand the challenges those same actors face when they must themselves confront other forms of life.

Heterogeneity of practice is, of course, a central difficulty for organizations like OSHA, EPA and EH&S. If laboratory workers all adhered to the same practices, they could be trained in the 'right' practices fairly easily, and regulatory agencies would then have little to do. In fact, as the relativist critique implies, what is 'right' is determined on the ground, in laboratories, in terms of what makes sense with respect to cost, convenience, knowledge, ability and desire, in addition to safety; laboratory workers may follow OSHA guidelines when they are being trained, or when an inspector is around, or when they are handling something especially dangerous, or perhaps when it simply occurs to them to do so, but they are very unlikely to follow them all the time, and they are almost as unlikely to see anything wrong in their consistent violations of these rules imposed from above.

One way in which my own practice as an ethnographer parallels those of the actors in my story lies in the very act of *telling stories* about cleanliness. Organizations like EH&S, as well as individual materials scientists, collect and propagate 'horror stories' about leaks, explosions, poisonings, fires, spills, and other accidents; such stories are circulated to trainee laboratory workers, handed out to professors for posting in their labs, displayed prominently on web sites, and brought up as cautionary tales during inspections. In this they resemble the 'war stories' told by Julian Orr's copier technicians, or the 'atrocity stories' told by Karin Knorr-Cetina's molecular biologists, in that they are used to socialize group members and pass on important information.[30] There are two major differences, though. First, like stories about war or atrocity in the literal sense, those told by EH&S personnel concern death and danger; and, consequently, they are used less to work through problems than to encourage compliance with pollution rules by making the possible results of noncompliance vividly clear. Remember Douglas' dictum that 'the ideal order of society is guarded by dangers which threaten transgressors';[31] it seems that materials scientists (and many other kinds of laboratory scientists) require rituals of cleanliness as well as myths about the objects of those rituals to enforce proper practice within the community.

Dirt and Social Danger

Let me illustrate the various strands of my argument thus far with what I feel is a representative anecdote. First of all, some background on the operation of Transmission Electron Microscopes. The TEM my informants use takes in specimens mounted on very small grids (0.0625″ radius). The grid and the specimen must be coated with some more-or-less electrontransparent material, usually carbon, and then ion-milled down to the right thickness so that the TEM can actually look inside the material and pick out structures such as grain boundaries, dislocations, decorations, and so on. Getting these two preliminary steps right is extremely tricky; too much or too little carbon and too much or too little ion-milling can mitigate the possibility of obtaining data from the specimen. In addition, both the specimen coater and the ion-mill are extremely cranky machines, and there is little way to tell if the sample is prepared correctly before going through the time-consuming process of inserting it into the TEM and firing the machine up.

On the occasion in question, Rudy had put a specimen into the TEM and prepared the microscope for operation, a task that takes almost an hour to complete. When he began obtaining images of the specimen, it became apparent to him that the specimen was undercoated; that is to say, the layer of carbon was not thick enough, and that therefore the specimen was 'charging up' as it attracted electrons from the TEM, causing the image to be occluded and endangering the possibility that data could be obtained without a tedious and time-consuming repetition of the carbon-coating and TEM run. To deal with the matter, Rudy left the microscope room and consulted with an acquaintance, an applied physics professor, who was sitting outside. After hearing the situation, the professor advised Rudy to leave the specimen in the TEM for a while with the electron gun off, but the vacuum pump running, in the hope that the carbon-based oils from the pump would eventually coat the specimen enough for it not to charge up.

Rudy politely listened to the advice and followed it. He told me later, though, that the applied physics professor's understanding of the TEM was suspect, and that his instructions would probably not work (and indeed, that was how he later construed the still-occluded images of the pump-oil-exposed specimen). The reason he gave for this was that the professor worked largely with the Ultra-High Vacuum Scanning Transmission Electron Microscope (UHV-STEM), and that the 'STEM people' operated under the belief that the regular TEM is a dirty machine where pump oils run amok in the vacuum chamber; Rudy felt that this was a mistaken belief, and that the time needed to coat the specimen by leaving it in the TEM would be of the order of several days.

What understandings of cleanliness can we see at work here? For one thing, this episode is exemplary of the use of dirt to shore up social distinctions and contain social danger: 'danger pressing on external boundaries; . . . danger from transgressing the internal lines of the system; . . . danger in the margins of the lines[; and] danger from internal contradiction'.[32] Most obvious here are the first and second of these; transgression of 'the internal lines of the system' is implicit in Rudy's fear of breaking a taboo on allowing a specimen to become too dirty. Hence, he uses the applied physics professor as an external resource to learn how to avoid such a transgression. In doing so, however, he places himself at the mercy of a foreign conception of dirt and contamination. Thus, though

Rudy felt that the applied physics professor was trying to be helpful, the materials scientist felt that his colleague was also displaying for his unfortunate TEM-using brethren the higher standard of cleanliness adhered to by UHV-STEM users. As Peter Clark and Anthony Davis point out, citing Norbert Elias, finicality about cleanliness can be a form of cultural capital.[33]

Interestingly, the *lack* of one kind of cultural capital may itself be regarded as a different kind of capital; thus, when directly asked about the issue of cleanliness in his work, Rudy would often say that it didn't pay to be too clean because that made any resultant findings, processes or products inapplicable for use by industry, which he felt to be an inherently dirty environment. That is, the knowledge that emerges from a specimen which has been ritually cleaned, like the knowledge that emerges from a ritually sacrificed laboratory animal in Michael Lynch's study,[34] is of a very abstracted sort; such abstraction may remove just those bits of information which are vital for connecting the laboratory to the 'real' world of industry, so materials scientists are often wary of making things overclean.

Of course, the same trick played by Rudy in evaluating physics as 'too clean' can be played by other disciplines in evaluating materials science. I observed one incident where Rudy and Paul were attempting to determine the nature of the crystalline substrate underlying their thin metal films; to do so they took a sample over to the X-ray diffractometer in the geology department, run by a CCMR technician. Rudy and Paul wanted to run several tests on the sample; the technician, however, merely wetted a finger and tasted the substrate, concluding that it was common salt. She then chided the materials scientists for not being enough like geologists, who, according to her, make it a practice to gain much of their preliminary information by taste. The dichotomy was clear, as was the evaluation: high-tech, high-cleanliness, lab-based, impractical materials science versus hands-on, low-cleanliness, field-based, common-sense geology. Thus, standards of cleanliness are relative and indexical; who is 'clean', 'dirty', or 'too clean' must always be articulated in a specific setting.

One of the 'common sense' ways dirt is used is as a kind of epistemological/ontological filter, often to pull knowledge away from epistemic 'danger in the margins of the lines'. Just the right amount of dirt can mark a piece of knowledge as the real thing; not enough (that is, findings which are 'too clean') can indicate error or deception. To take another microscope example from Rudy's work, much of his time was spent creating very small (nanometer-scale) but perfectly regular grid structures inside and on the surfaces of thin films; in looking at surface features using an Atomic Force Microscope (AFM), however, he was consistently distrustful when he, in fact, observed such a *perfect* grid. According to him, a perfectly regular pattern was most likely to be artefactual, caused by a problem in the AFM's sampling algorithm, and quite unlikely to be due to his own diligence in preparing the specimen correctly. A slightly irregular grid pattern, however, was likely to be 'real' and caused by his own work overlaid by some inevitable, and tell-tale, disruption and contamination.

In one incident I observed, Paul, then quite new to the Sitman group, and hence still unfamiliar with its practices and knowledge, excitedly showed Rudy a picture of what he believed to be the desired grid structure of dislocations taken with the TEM. The TEM, however, produces images that are even more difficult to interpret than the AFM's, and after examining Paul's photographs Rudy informed him that the grid was too perfect to be what they were looking for, and that instead it represented an optical effect (a Moiré pattern) produced by the microscope. A real grid would almost certainly show some disorder due to irregularities in its handling and impurities in its makeup. Again, this shows the use of standards of cleanliness both in mapping out the internal lines of the system (third-year graduate student teaching first-year) and in rescuing knowledge from the ambiguous margins of reality. Mary Douglas hints at this in describing the creative power of imperfection:

> Granted that disorder spoils pattern, it also provides the material of pattern. Order implies restriction; from all possible materials, a limited selection has been made and from all possible relations a limited set has been used. So disorder by implication is unlimited, no pattern has been realised in it, but its potential for patterning is indefinite. This is why, though we seek to create order, we do not simply condemn disorder. We recognise that it is destructive to existing patterns; also that it has potentiality.[35]

This episode shows, then, that if order is the objective, within the laboratory group such order must still display its origins in the patterning of disorder (through the deliberate actions of the materials scientist), or it risks being dismissed as an unreal artefact.

Dirt can also work as a measure of the durability of a finding. That is, Rudy often claimed that he preferred to carry out initial experiments in a more lax, 'dirty' manner, betting that if he found what he was looking for it would definitely be durable enough to make experimental yield worthwhile (and also more likely to appear under industrial conditions). Dirt here seems to be an 'even though' gate; if the desired finding appears 'even though' dirt is present, then the finding will be more durable and, for practical reasons, more valuable. I suspect other researchers use the opposite tactic – that is, they find what they are looking for under very clean conditions and then work to make it more durable – but it is interesting to note the existence of Rudy's strategy.

The anecdote about Rudy and the TEM points up another important feature of the way materials scientists regard pollution, namely the complex interactions between different kinds of potential contaminants; indeed, this indicates the rôle of dirt in creating, and resolving, dangers of what Douglas would call 'internal contradiction'. The carbon which coats TEM specimens is 'clean' so long as there is not too much of it, and in fact, the application of it to the specimen is a kind of cleansing ritual, in that it wards off the image occlusion caused by the electrons charging up the material. The electrons, therefore, are 'dirty', so long as they interact with the specimen in the wrong way; they have to interact to some extent, however, since they are the means by which the TEM produces images. Thus the carbon can become a form of dirt if too much is deposited and it occludes the image by preventing electrons from interacting with the specimen in the proper way; this is why pump oils are generally regarded negatively. Materials scientists, therefore, have to navigate a treacherous path between different kinds of dirt, using one kind to ward off another. This is made all the more complicated by the fact that, since dirt can occur at any epistemic level – at any 'externality' (in Trevor Pinch's terms) or 'modality' (in Bruno Latour's and Steve Woolgar's)[36] – TEM users have to be wary of contamination of the material specimen, of the chamber housing the electrons that pass through the specimen and on to a screen, of the representation of the specimen those electrons deliver to the screen, and of the photographs that are taken of the screen and then passed along as the end-products of TEM use.

As interdisciplinary scientists and engineers, my informants continually cobbled together scraps of knowledge from an eclectic variety of fields for a wide range of uses. At the lab bench, they (perhaps more than most) manufactured and characterized their materials using a panoply of borrowed practices: one day they might scrounge around in sample cabinets looking for 15-year-old specimens to reuse, the next they might borrow an instrument in a friend's lab to get a quick look at one of their samples, and the next they might buy cheap nail polish at the corner drug store to use as sealant. What is perhaps surprising in this, though, is that objects and processes that might potentially be, or already were, seen as contaminated or contaminating, were just as available for use as any other resource.

Indeed, all three of the examples of scrounging I just cited are also instances of dirt in action. Nail polish is likely to contaminate any piece of gold film on salt substrate to which it is applied; to be sure, time after time Rudy and Paul started AFM runs only to find that the film surface was too contaminated with blue organic goop for any good images to be taken. But the polish was needed in an attempt to etch away the salt substrate from one of two films that were bonded together; the salt, once necessary to keep the film in place, had become worse than useless. Indeed, once the films had been bonded, the salt became matter out of place and some process was needed to cleanse it away; more AFM runs were ruined by unacceptably large flecks of salt still adhering to the film surface than by misapplied nail polish. Cleaning rituals begin with dirt and they end with dirt; it's merely a matter of which kind of dirt is acceptable (though still not desirable) for the present goal.

Likewise, going into someone else's lab can lead to exposure to all sorts of dangerous dirt; people in other groups may, for example, deal in quite different kinds of pollution from one's own. EH&S inspectors are particularly aware of this, and their methods are quite different when entering a lab that makes silicon semiconductors (where toxic chemicals may be rare, but exposed wires and sparking outlets may be a danger) from when they are entering a lab that makes polymers (where electrical hazards may be nonexistent, but toxins and carcinogens may abound). Worse still, different groups may have incommensurable standards of cleanliness and knowledge about various kinds of dirt; thus, my informants almost always preferred to deal with dirt that they knew and believed they understood, rather than 'new' dirt.

For example, I once accompanied Angus as he visited a chemistry group with which he was in contact in order to use their X-ray diffractometer (XRD). As one of the chemists was placing Angus' material in the XRD, he first coated it with a small amount of silica gel; this made Angus somewhat agitated, since he knew the gel would diffract X-rays (although he didn't know specifically how much) and he was afraid that the results he was interested in would be masked by this unfamiliar, albeit apparently useful, kind of dirt. The chemist merely laughed and assured Angus that he had nothing to worry about, that the gel would only register in an otherwise uninteresting part of the spectrum (although when Angus got the results back he construed them as showing that the gel had, in fact, done what he feared it would). Figure 3, on the other hand, shows the converse of this problem; it is just as much a danger to have other people coming into one's own lab as to go into someone else's oneself.

FIGURE 3
'Down with Impurity'

The figure shows the entrance to a room containing several microscopes, a technician's office, and some other equipment – the white object on the floor is a static pad, covered with the footprints of people who did not put on the foot coverings in the boxes next to the door. The woman in the photograph is Carrie Nation, the 19th-century temperance activist.

Dirt as Discriminator and Generator of Explanations and Anomalies

My fundamental point is this: materials scientists, working in a world in which pollution has many valences, must strike a balance between making things *too clean* and *not clean enough*. This bears clarification: *not only is what is to count as polluting variable, but the desirability of purification is itself contestable. Sometimes it is best not to remove contaminants, nor to transform a polluted thing into an unpolluted one*. That is, even when materials scientists are able to stabilize-for-the-moment what things to count as contaminating, they may decide that the work needed to purify a polluted part of the world is burdensome or even counter-productive, and that dirt may even be a way of 'thinking out of the box', where the *introduction* of pollution is often a key strategy. To demonstrate this perhaps counter-intuitive situation I want, finally, to revisit a recurring science studies theme, replication.

The classic investigation of replication in science, Harry Collins' *Changing Order* (1985),[37] makes clear that replication, in the sense often posited by philosophers of science, is quite rare. For Collins, 'isomorphic' replication (exact copies of procedures) is common only in situations of 'normal' (rather than 'extraordinary' or 'revolutionary') science, and even then only in 'non-test situations' (such as making a new TEA-laser).[38] My informants, however, make isomorphic replication (or its near equivalents) a central part of their methodology. Much of their time is spent repeating exactly the 'same' experimental techniques in order to build up libraries of materials from which to harvest further data and test the aptness of their ideas and techniques. Nevertheless, Collins' observations still hold; laboratory practice is so variable, and the results of experiments often so ambiguous, that interpretive flexibility is still apparent. Importantly, dirt is an integral part of this flexibility.

To see how this works, imagine a hypothetical situation amalgamated from the Sitman group's experimental method. Say, for instance, that Angus wanted to test whether the phase of platinum he was looking for appears when he runs a sample in the hot press at 1100°C for 15 hours; to test this procedure he would want to run 8 or 10 samples in approximately the same way, collecting data points that could then be compared to 8 or 10 specimens run at, say, 1500°C for 10 hours. After two runs at 1100°C, each sample could either have the phase present (a 'success') or not (a 'failure' – I ignore for now the interpretive ambiguities of deciding whether the phase is present or not). Let's compare how the two runs are evaluated when (1) both samples are taken to be clean, and (2) when one of the samples is thought to be contaminated in some way.

If both specimens come through the technique successfully, some objective has clearly been reached no matter what. If both of them are clean, nothing more has been learned than that the technique apparently works. If at least one of them can be labelled dirty, however, there is the bonus of knowing that the dirt apparently has no effect. Here we have an example of dirt acting as an 'even though' gate – the phase appeared in both 'even though' one sample may have been contaminated. As Rudy explained, the materials scientist's work is thereby made more valuable by its ability to withstand contamination.

If one specimen fails and one succeeds, the results are obviously more mixed. This is doubly so if both specimens are taken to be uncontaminated. Does the procedure really only work half the time? Or is it that it hasn't worked at all, and the 'success' of one specimen is merely an artefact? The materials scientist has no way of discriminating between the specimens so as to explain the difference in the experimental outcomes. Ambiguity has increased, rather than lessened. Henry remarked to me, in annoyance, that this is the position he usually found himself in when comparing different specimens. Laboratory work is so unstable that most sets of specimens show a much wider variability than experimenters would prefer.

If one of the specimens can be treated as contaminated, however, the degree of ambiguity immediately drops. If it is the dirty specimen that failed, then everything is straightforward – it most likely failed because of its contamination. If we substitute the word 'scientifically' for the word 'morally', we have exactly the sort of situation Douglas describes: 'when a situation is morally ill-defined, a pollution belief can provide a rule for determining *post hoc* whether infraction has taken place or not'.[39] That is, the fact of pollution often only comes into being if it is demanded by the ambiguity of the situation (that is, if something is deemed not to be working as it should be).

I saw several instances of this when Rudy and an undergraduate were characterizing specimens using the AFM. The AFM is normally extremely sensitive to vibration, and there is, in fact, sound-absorbing material covering all four walls of the room in which it is housed. Often, though, Rudy would leave the door to the room open, allowing substantial noise from the adjoining room to enter. If, however, the AFM were being cranky and images could not be obtained, he would walk over to the door and shut it, thereby creating the *post hoc* fact of noise pollution where, when the AFM was 'working', such pollution did not exist.

If it is only the clean specimen that fails, however, things become somewhat more interesting. Here is where dirt can be at its most helpful. For what is it that the materials scientist can point to that discriminates one sample from another? Often, only the contamination that was introduced during the experiment. He or she can now investigate systematically the effects of such 'dirt' to see how it may have caused the contaminated sample to succeed where the clean one did not; or perhaps, like Jordan and Lynch's immunoassay technicians, they may leave the contamination unexamined but incorporate it into future experimental ritual, as an act hovering between belief-based superstition and knowledge-based specimen preparation.[40] Either way, dirt becomes a resource for discrimination of experimental set-up, an explanation of experimental outcome, and a potential site for future research. Obviously, things may not pan out, and the fact of contamination may become irrelevant once again; but if the particular kind of dirt involved continues to be taken to contribute to successful outcomes, it may become a bona fide part of materials science knowledge. That is, *the fact of pollution can act not only as* post hoc *indicator of infraction, but it can also be used, symmetrically, to discriminate and explain success and failure*.

Admittedly, this is not always the case. Sometimes materials scientists are rather more likely to ascribe both success and failure to chance variation, and continue working as they were before; but the phenomenon I am trying to convey certainly occurs. As I mentioned previously, Angus at one point faced a situation where he obtained strikingly different results for two runs of the same experiment; when he re-examined his materials, the only difference between them that he found was that one of the batches of platinum he was using was contaminated with residue from sweat and finger oils. Discovering the pollution allowed him to discriminate and explain his previous results; indeed, because the contaminated batch had worked somewhat better, he began to look for *more* similarly polluted platinum.

Examples of such serendipities through pollution have entered the lore of a number of scientific disciplines; it is important to note, however, that they can only be considered serendipities because the conditions for their existence have been prepared by socially constructed notions of what is clean and what is not, what is a successful experiment and what is not. Interestingly, this variability in the decision as to whether to follow up clues offered by contamination is taken by many materials scientists to be a matter of personality. Indeed, cleanliness is the site for much 'personality talk' in materials science: individuals are taken to be inherently clean or messy, characteristically good or poor at performing pollution rituals (people often tell me that in some labs, the products of an individual's work can be identified merely by the marks of how, and to what extent, they have cleaned a specimen), and habitually bold or cautious in how they follow up dirt-based anomalies.

If both specimens fail and both are clean, the situation is at its most grim. There is no way to ascribe failure to some extraprocedural fact such as pollution. Instead, one can only conclude that the method will not produce the desired outcome. Compare this total nonsuccess with the case for two failures with one of the specimens contaminated. Obviously, this is still a frustrating result. However, it may still be possible to claim that true replication has not taken place, since one specimen was contaminated and therefore does not count. Of course, if the procedure continues not to yield the desired result, it may be abandoned. In that case, though, the experimenter can point to the polluted status of the specimens, and say that the method is *in principle* workable, but that the techniques do not at present exist to make materials clean enough for them to survive the procedure. In the long run, though, such an account may have little currency, since there may be a limited lifetime for explanations that pass responsibility for dirt to other parties.

The conclusion, then, is that dirt is helpful, since more is learned in each case when one of the specimens is thought to be contaminated. One (clearly nonsensical) way of taking this is that materials scientists go around contaminating exactly half their specimens; a more reasonable interpretation is that they use dirt, and imputations of contamination, as positive resources (often *post hoc*) in making knowledge. The variability of their practice means that specimens will generally, in hindsight, lie along a continuum of cleanliness, and that there will almost always exist some incident in the career of a specimen which can be seen, after the fact, as having polluted it. That is, given the ambiguities and contradictions of dirt, some matter can almost always be imputed to be 'out of place' in one way or another. In many cases, however, such evaluations are not seen as being made simply with the benefit of hindsight; as Thomas Kuhn and a host of others have pointed out, scientists generally have a rough idea going in how an experiment will turn out, and cleanliness is one factor constituting such expectations. An anomalous result may be seen as the likely outcome of an experiment run with a specimen that has had an anomalously dirty career. Still, though they rarely make hard and fast judgements about the cleanliness of a specimen *before* an experiment (at least not for specimens they have some hope of succeeding with), materials scientists quite regularly make such judgements after the results are in; and when they do, those judgements will, I think, have a propensity to fall out in the way I have described.

Thus, as Mary Douglas says, 'dirt, which is normally destructive, sometimes becomes creative'.[41] We have seen throughout how dirt can be used as a positive resource; but in the examples above, such as Angus' serendipitous experience with the platinum, we see dirt leading directly to the creation of new knowledge. In these cases, *cleanliness* has become restrictive: that is to say, 'purity is the enemy of change, of ambiguity and compromise'.[42] Dirt here helps to create the perception of anomaly; as a phenomenon, it acts much like what Hans-Jörg Rheinberger calls 'generators of surprises' or 'question-generating machines'.[43] Such anomaly generators allow for unforeseen possibilities simply because they present challenges to the current paradigm; as such, materials scientists take them to be thoroughly necessary guides to the unpredictable. If materials scientists could always avoid dirt and disorder, and invariably make materials obey their demands, they would quickly achieve their goals, but they would also quickly exhaust the need for their work, since their paradigm would degenerate rapidly without the creative outlets provided by pollution.

Cleanliness, therefore, is a complicated but important issue in materials science. Often enough, dirt is indeed destructive; but our knowledge of the discipline will be incomplete if we leave it at that. We will have missed all of the ways in which dirt is used positively to create knowledge. This is so, not only for materials science, but for a wide range of disciplines in which contamination is an important concept. While we have much high-quality anthropological work on pollution and taboo at hand, it only makes sense to expand our understanding of this issue to more and more of the areas in which it plays a vital rôle, and to integrate our knowledge about this area of cultural life with our analysis of the social world of science and engineering.

Notes

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1. Some important laboratory studies in which purification and related topics play a rôle include: Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, revised edn, 1986); Hugh Gusterson, *Nuclear Rites: A Weapons Laboratory at the End of the Cold War* (Berkeley: University of California Press, 1998); Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists* (Cambridge, MA: Harvard University Press, 1988); Trevor Pinch, *Confronting Nature: The Sociology of Neutrino Detection* (Dordrecht: Reidel, 1986); Karin Knorr-Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, MA: Harvard University Press, 1999); Michael Lynch, *Art and Artifact in Laboratory Science: A Study of Shop Work and Shop Talk in a Research Laboratory* (London: Routledge & Kegan Paul, 1985).
2. Pearl Katz, 'Ritual in the Operating Room', *Ethnology*, Vol. 20, No. 4 (October 1981), 335–50; Stacia E. Zabusky, *Launching Europe: An Ethnography of European Cooperation in Space Science* (Princeton, NJ: Princeton University Press, 1995), 208; Barbara Rawlings, 'Coming Clean: The Symbolic Use of Clinical Hygiene in a Hospital Sterilising Unit', *Sociology of Health and Illness*, Vol. 11, No. 3 (1989), 279–93; Stefan Hirschauer, 'The Manufacture of Bodies in Surgery', *Social Studies of Science*, Vol. 21, No. 2 (May 1991), 279–319.
3. Kathleen Jordan and Michael Lynch, 'The Sociology of a Genetic Engineering Technique: Ritual and Rationality in the Performance of a "Plasmid Prep"', in Adele E. Clarke and Joan H. Fujimura (eds), *The Right Tools for the Job: At Work in the Twentieth-Century Life Sciences* (Princeton, NJ: Princeton University Press, 1992), 77–114.
4. Mary Douglas, *Natural Symbols: Explorations in Cosmology* (London: Barrie & Rockliff/ Cresset Press, 1970); Douglas, 'Environments at Risk', *Times Literary Supplement* (30 October 1970), 1273, reprinted in Douglas, *Implicit Meanings: Essays in Anthropology* (London & Boston, MA: Routledge & Kegan Paul, 1975), 230–48; Douglas, *How Institutions Think* (Syracuse, NY: Syracuse University Press, 1986); Douglas (with Aaron Wildavsky), *Risk and Culture: An Essay on the Selection of Technical and Environmental Dangers* (Berkeley & London: University of California Press, 1982); Douglas, *Risk Acceptability According to the Social Sciences* (New York: Russell Sage Foundation, 1985); Douglas, *Risk and Blame: Essays in Cultural Theory* (London & New York: Routledge, 1992).
5. David Bloor, 'Polyhedra and the Abominations of Leviticus', *British Journal for the History of Science*, Vol. 11, Part 3 (November 1978), 245–72; Barry Barnes and Steven Shapin, 'Where is the Edge of Objectivity?' [Review of Douglas, *Implicit Meanings*], *ibid.*, Vol. 10, Part 1 (March 1977), 61–66; Michiel Schwarz and Michael Thompson, *Divided We Stand* (Philadelphia: University of Pennsylvania Press, 1990). Bloor's discussion of polyhedra uses Douglas' ideas about contamination, but not with reference to material contamination in laboratory settings.
6. Mary Douglas, *Purity and Danger: An Analysis of Concepts of Pollution and Taboo* (London: Routledge & Kegan Paul, 1966).
7. Mary Douglas, personal communication (July 2000).

8. For a fine-grained analysis of a field science in which 'dirt' (in both a literal and an abstract sense) plays a rôle, see Charles Goodwin, 'Professional Vision', *American Anthropologist*, Vol. 96, No. 3 (September 1994), 606–33; this tails well with the same author's description of purification practices in a laboratory setting in Charles Goodwin, 'The Blackness of Black: Color Categories as Situated Practice', in Lauren B. Resnick, Roger Saljo, Clotilde Pontecorvo and B. Burge (eds), *Discourse, Tools, and Reasoning: Essays on Situated Cognition* (Berlin: Springer-Verlag, 1997), 111–42.
9. All names in this study are pseudonyms. In addition, some details of my informants' research topics have been changed to preserve their anonymity.
10. Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), 205.
11. For work on the history and theory of the engineering sciences, see Ronald Kline, 'Construing "Technology" as "Applied Science": Public Rhetoric of Scientists and Engineers in the United States', *Isis*, Vol. 86, No. 2 (June 1995), 194–221; Edwin T. Layton, Jr, 'American Ideologies of Science and Engineering', *Technology and Culture*, Vol. 17, No. 4 (October 1976), 688–701; Terry S. Reynolds, 'Defining Professional Boundaries: Chemical Engineering in the Early 20th Century', *ibid.*, Vol. 27, No. 4 (October 1986), 694–716; and Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, MD: Johns Hopkins University Press, 1990).
12. Douglas, *Purity and Danger*, op. cit. note 6, 36.
13. 'Technological determinism' in the sense of an 'internal technical logic' or an 'autonomous logic of development', as laid out in Wiebe E. Bijker and John Law, 'General Introduction', in Bijker and Law (eds), *Shaping Technology/Building Society: Studies in Sociotechnical Change* (Cambridge, MA: MIT Press, 1992), 1–14, at 8.
14. *http://www.intel.com/au/eng/s2s/fab.htm*
15. NSF Panel on Atomic Resolution Microscopy, 'Atomic Imaging and Manipulation for Advance Materials: A Proposed Program on Atomic Scale Mechanisms, Imaging, and Manipulation' (Washington, DC: NSF, April 1993), 9.
16. See, for instance, Peter Clark and Anthony Davis, 'The Power of Dirt: An Exploration of Secular Defilement in Anglo-Canadian Culture', *Canadian Review of Sociology and Anthropology*, Vol. 26, No. 4 (August 1989), 650–73.
17. This is akin to Klaus Amann's observation that the first mouse he saw in a genetics lab was not a 'lab mouse' but an ordinary house mouse. Both mice might be subject to mutations and other 'impurities', but only the lab mouse becomes an object of investigation. Klaus Amann, 'Menschen, Mäuse und Fliegen', *Zeitschrift für Soziologie*, Vol. 23, No. 1 (February 1994), 22–40.
18. Douglas, op. cit. note 6, 9.
19. One by-product of studying laboratory dirt is that I've heard many anecdotes about serendipities involving various kinds of contamination. Commonly, these anecdotes involve the transformation of some kind of pollution from 'ordinary' to 'scientific' dirt. For instance, one story revolves around a technician's daily lunch routine and the discovery of the rôle of fish oil in a certain chemical reaction.
20. Douglas, op. cit. note 6, 69.
21. The vermiculite is needed because moisture is thought of as condensing on or being absorbed by some kinds of materials; thus, a specimen left in a vessel without vermiculite will degrade over time due to the action of the moisture in the air around it. This is an excellent example of time as an operator of pollution – nothing is visibly being done to the specimen, yet it is treated as being in danger from the ravages of an enemy that is constantly at work.
22. Jordan & Lynch, op. cit. note 3, 107. 'Translucent boxes' are techniques or artefacts that seem 'black-boxed' in some respects, but which are continually reopened and reinterpreted according to local contingencies.
23. Circulating in a 'moral economy' somewhat like that of fruit flies in Robert Kohler, *Lords of the Fly* (Chicago, IL: The University of Chicago Press, 1994), Chapter 1; see

also W. Patrick McCray, 'Large Telescopes and the Moral Economy of Recent Astronomy', *Social Studies of Science*, Vol. 30, No. 5 (October 2000), 685–711.
24. Douglas, op. cit. note 6, 7.
25. Dan Jorgensen, 'Echidna and *Kuyaam*: Classification and Anomalous Animals in Telefolmin', *Journal of the Polynesian Society*, Vol. 100, No. 4 (December 1991), 365–80, at 375.
26. Hirschauer, op. cit. note 2; H.M. Collins, 'Dissecting Surgery: Forms of Life Depersonalized', *Social Studies of Science*, Vol. 24, No. 2 (May 1994), 311–33; followed by Stefan Hirschauer, 'Towards a Methodology of Investigations into the Strangeness of One's Own Culture: A Response to Collins', ibid., 335–46; then Nicholas Fox, 'Fabricating Surgery: A Response to Collins', ibid., 347–54; Michael Lynch, 'Collins, Hirschauer, and Winch: Ethnography, Exoticism, Surgery, Antisepsis and Dehorsification', ibid., 354–69; and finally Collins, 'Scene from Afar', ibid., 369–89. See note 4 (p. 367) of Lynch's contribution to this debate for references to its roots in the writings of Winch and Wittgenstein.
27. For the concept of 'habitus', see Pierre Bourdieu, *The Logic of Practice*, trans. Richard Nice (Stanford, CA: Stanford University Press, 1990), 52ff.
28. Michael Lynch, 'Discipline and the Material Form of Images: An Analysis of Scientific Visibility', *Social Studies of Science*, Vol. 15, No. 1 (February 1985), 37–66.
29. Cornell Nanofabrication Facility, 'Laboratory Usage and Safety Manual for CNF' (Ithaca, NY: March 1999), 15. Clean-room culture, however, is considerably more stringent than materials science lab culture in general. As we shall see, all dirt, including contamination originating from the bodies of laboratory workers, can become a positive resource. At one point in Angus' investigations, for instance, he discovered that low-grade platinum actually facilitated his experiments better than a higher-grade because it contained a residue of salts and organic matter from sweat and finger oils.
30. Knorr-Cetina, op. cit. note 1, 106; and Julian E. Orr, *Talking About Machines* (Ithaca, NY: Cornell University Press, 1996), 125ff.
31. Douglas, op. cit. note 6, 3.
32. Ibid., 123–24.
33. Clark & Davis, op. cit. note 16, 664.
34. Michael Lynch, 'Sacrifice and the Transformation of the Animal Body into a Scientific Object: Laboratory Culture and Ritual Practice in the Neurosciences', *Social Studies of Science*, Vol. 18, No. 1 (February 1988), 265–89.
35. Douglas, op. cit. note 6, 95.
36. Trevor Pinch, 'Towards an Analysis of Scientific Observation: Externality and Evidential Significance of Observational Reports in Physics', *Social Studies of Science*, Vol. 15, No. 1 (February 1985), 167–87; Latour & Woolgar, op. cit. note 1, 77.
37. H.M. Collins, *Changing Order: Replication and Induction in Scientific Practice* (London: Sage, 1985; Chicago, IL: The University of Chicago Press, 2nd edn, 1992).
38. Ibid., 170.
39. Douglas, op. cit. note 6, 134.
40. Jordan & Lynch, op. cit. note 3, 98.
41. Douglas, op. cit. note 6, 160.
42. Ibid., 163.
43. Hans-Jörg Rheinberger, *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube* (Stanford, CA: Stanford University Press, 1997), 32.

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