Chesterene Cwiklik,[1] *B.S.*

An Evaluation of the Significance of Transfers of Debris: Criteria for Association and Exclusion*

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ABSTRACT: Several criteria are proposed for making decisions about comparing sets of debris involving the transfer of non-component particles and fibers—those produced from something other than the item itself—using a model based upon rudimentary set theory. Decisions about the significance of an association or an exclusion based upon trace evidence require an evaluation of debris in its context; reference points for such evaluation are presented. Samples of debris from the sites relevant to the event under investigation must be available, as well as debris standards from the usual environments of the people involved, and must be adequate to permit a determination of normal versus foreign debris.

Criteria are proposed for establishing contact based upon corresponding sets of particles and fibers, for excluding contact in the absence of corresponding particles or fibers, and for refraining from making either an association or an exclusion. Conditions for reaching qualified conclusions or other types of associations when these criteria are only partially met are also discussed; conclusions may sometimes be reached if potential sources for debris particles and fibers can be found. Decisions about the strength of an association or an exclusion based upon comparisons of non-component debris particles and fibers can be made by reference to the criteria for reaching a conclusion. The criteria can be tested via Bayes' Theorem. The analysis itself is based primarily upon light microscopy, although other methods may be used as well. Case examples are presented.

KEYWORDS: forensic science, criminalistics, trace evidence, transfer, debris, dust, particles, fibers, associative evidence, evaluation, microscopy, sets, probability, Bayes' Theorem

Many of the pioneers of forensic science (1–6) and contemporary industrial microscopists studying contamination problems (7) have recognized the usefulness of sets of debris as providing information that could not be obtained in any other way. Archaeologists have long studied sets of debris, referred to as assemblages of artifacts; these terms are sometimes borrowed by microscopists (7,8). Debris has also received attention in current forensic literature (1–6,8–13), however, there has been little attention to transfers of debris. Practicing forensic scientists do perform comparisons of sets of debris, but most of the current literature and methods development is directed toward more specific identification of the original sources of the transferred particles and fibers rather than toward the evidentiary value of the debris as a whole.

When trace evidence is transferred from one item to another during contact, the material transferred includes particles and fibers abraded, flaked, broken, or torn from the items themselves as well as other particles and fibers that have collected on the surface of each item prior to their contact. The latter particles and fibers are non-component debris: not an intrinsic (component) part of the items themselves. Their transfer is referred to as secondary, tertiary, and higher degrees of transfer: indirect transfer from the source item. The articles published on this topic include examples demonstrating the investigative value of debris (1–4), a caution against ascribing significance to stray fibers found amongst debris (14), studies of secondary human scalp hair transfer (15) and secondary and tertiary dog hair transfer (16), studies of secondary fiber transfer (17,18) and a case study treating the information value of secondary and tertiary fiber transfers (19).

Often viewed simply as posing a problem for interpretation, this type of transfer can provide information about contact (16,19). Because the non-component debris found on an item reflects the individual history of that item, it has the potential for uniquely identifying that item, and when transferred, for providing information about contact that is far more specific than would otherwise be possible. In order for these types of comparisons to have wider use, formal criteria for evaluating the significance of the results of debris comparisons are needed, and are proposed in this paper.

The Nature of Debris and Definition of Sets of Debris

The debris found in a given location, for example, the master bedroom of a particular house, is a set of particles and fibers composed of smaller sets referred to as sub-sets. The set of members of the same type is referred to as a family. In the case of debris, each set includes families unless it comprises stray particles and fibers, or unless only a small sample of the debris is available.

Sets of particles and fibers are those that share some common conditions, in this case, a common site, means of particle or fiber production or means of transport. One sub-set of particles and fibers is produced by processes occurring in that room, such as hairs and skin flakes from the occupants, feather barbules from pillows, carpet fibers and fibers from clothing in the wardrobe. Several more sub-sets of particles and fibers deposited in the room are produced by processes that occur elsewhere and are shed from clothing. There is also a sub-set of debris from aerial transport, such as soil, traffic dust, pollen and spores, insect parts and so on. Lastly, there are debris particles and fibers that are produced by occasional events or visitors.

Unless something is dropped and spilled, such occasional or accidental events usually result in few particles or fibers of any

[1] Cwiklik & Associates: Microscopy and Forensic Consulting, 2400 Sixth Avenue South #257, Seattle, WA.

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given type. The debris produced by the accidental or occasional drops or spills does add a time line to the record of daily life, and is thus a historical record. However, it is the debris that is produced by repetitive processes that is the record of daily life, and thereby characterizes that location. "Dust contains in small all the things that surround us (Leibig) (5)." Transfers of such debris can be evidence of contact. "For the microscopically finest particles that cover our clothing and our bodies are the mute witnesses to each of our movements and encounters (Edmond Locard) (5)."

Debris found on clothing includes debris from other clothing worn by the same person, as well as debris produced in and transferred by the processes described above, to the residence, work place, and other environments that a person frequents. Transfer of the latter particles could be expected to occur in the manner proposed by Grieve and Biermann for experimental transfer of clothing fibers, i.e., primarily through intermediary articles of clothing, and only secondarily by direct transfer (18). One would also expect articles such as bedding and furniture to serve as intermediaries for transfer.

When debris on such items is examined as potential evidence, it is useful to think about the role of each subset of particles and/or fibers as it affects the significance of any correspondence with debris on other items.

Criteria for Establishing and Excluding Contact

When fibers like the component fibers of a garment are found on another garment, this supports the hypothesis that the two garments were in contact. However, when non-component fibers or other particles of debris like those on one item are also found on another item, the significance of such correspondence is less clear. The forensic scientist is faced with deciding when a comparison of sets of debris that includes non-component particles and fibers permits a conclusion and when it does not, and must furthermore decide what the conclusion should be. The following criteria are proposed for making decisions about comparing sets of particles and/or fibers involving the transfer of non-component debris; each will be illustrated by case examples later in this paper. To avoid awkwardness, the term "particle" will be used to include both particles and fibers.

Conditions for Reaching Conclusions about Contact

To permit conclusions establishing contact, there must be enough particles, there must be enough types of particles, and the correspondences must significantly outweigh the non-correspondences. To permit conclusions excluding contact, there must be enough particles on the item, and the expected particles, given contact, must be absent. "Enough particles" implies that the great majority of particles are more numerous than such stray or random particles as those that might have "floated" onto the substrate. "Enough types of particles" implies sufficient properties for a distinctive characterization of the set of debris. Sub-sets of particles consisting of one or two members of a single type are considered "random particles" in a set of non-component debris, as are those that are very few in number in comparison with other types of particles. "Correspondence" means that a specific type of fiber or particle found on one item is also found on the other item being evaluated for contact. "Non-correspondence" refers to a specific type of particle or fiber being found on one item but not on the other. "Substrate" is the fabric or painted surface or other material on which the debris is found.

Conditions for Establishing Contact

Contact between two items can be established in the presence of corresponding particles under the following conditions: A) when the probability of the particles being there randomly without true correspondence is low (the probability of transferring, persisting, and being detected is given, as particles were found); B) when there are enough particles and enough corresponding particles; C) when there are enough types of particles; D) when the correspondences significantly outweigh the non-correspondences; and E) when the particles of potential significance could not be from the environment where the questioned sample was found or normally kept. Condition a would not usually be met, for example, with common white cotton fibers and blue denim cotton fibers, which are nearly ubiquitous in debris in North America.

When conditions A, B, and C are met, the set of particles may well be unique to a specific location or person. When conditions D and E are met as well, and when the corresponding debris includes particles like the substrata of both items, this can constitute proof of contact. There is no simple rule to indicate exactly when it would be proof. The implications of meeting all the conditions for establishing contact finally depend upon the context of the debris, as discussed later in this paper.

When Conditions for Establishing Contact Are Not Fully Met

Contact cannot be conclusively established despite the presence of corresponding particles of non-component debris if any of the conditions A through E are not met. In that case, no conclusion should be reached based upon correspondence of debris particles alone. It may still be possible to reach less definitive conclusions if certain other conditions are present. Even if not all the conditions for establishing contact are met, qualified conclusions may be reached if there are particles among the debris like those of the substrate of the other item, or like the substrata of potential original sources of predominant debris particles. "Original source" refers to the object from which the debris particles in question were produced, and is independent of whether the transfer is primary, secondary, or tertiary and so on. This is further discussed below.

Conditions for Excluding Contact

Contact can be excluded in the absence of corresponding particles under the following conditions: A) when the probability of transferring would be high had contact occurred; B) when the probability of persisting would be high had material been transferred; and C) when the probability of detection would be high had material been transferred and retained. It is not necessary to consider the probability of transferred particles being there, as this would be zero or small when either nothing corresponding is found or the amount found is insignificant. It is not necessary to know numerical probabilities to apply this criterion; it is sufficient to know that the probabilities of transfer, persistence and detection are high rather than low or something in between. In most cases, this knowledge is within the casework experience of an analyst who frequently examines debris on clothing and other items; the knowledge that is "experience" can be supplemented by experiment.

When Conditions for Excluding Contact Are Not Met

Contact cannot be excluded despite the absence of corresponding particles when the probability of transfer or persistence or detection would be low. If it is not known whether those probabilities would be high or low, a few experiments might be performed to find out, using types of debris and substrata similar to the evidence materials; otherwise, no conclusion should be reached.

Discussion

Evaluating Corresponding Debris

When There Is Additional Debris on One Item

When correspondence between debris on one item with debris on a second item is high, but additional debris is found on the second, it is important to know if the additional debris could be from the usual environment of the second item, from the environment where it was found, or from events subsequent to the time when any transfer would have occurred. If there is a reasonable hypothesis from the history of the item to explain why the additional debris did not transfer, one may be able to reach a conclusion. For example, if debris in a car thought to have been involved in a rural crime exhibits a high degree of correspondence with crime scene debris except for some beach sand found in the car but not at the crime scene, it would be possible to make a strong association if one were to know that the car had since been driven to the beach. If this were not known, it would still be possible to make an association, with a proviso regarding the additional particle types.

When Conditions for Establishing Contact Are Not Fully Met but Potential Sources of Non-component Debris Are Available

When all the criteria for establishing contact have been met, it is not usually necessary to know the potential original sources of the non-component debris particles (i.e., the substrata from which those particles were first produced); this is discussed in the Methods section. However, when the possibility of contact between two items is being investigated and neither item is a rich source of substrate particles, it may be useful to study the debris further even if all the conditions for establishing contact have not been met. Sometimes a conclusion may be reached if potential original sources for the predominant debris particles are found. This is illustrated in Case Example 3, and in published case studies (12,19–22).

When Little or No Transfer of Substrate Particles Is Observed

If no transfer of substrate particles is observed or if the transfer is from one item only of two that may have been in contact, it may be that the substrata do not shed much. This can be evaluated by observing whether particles of the item itself are found among its debris, or in the case of fibers, it may be helpful to conduct a shedding test (23).

When Correspondence of Debris May Be due to Contact of Both Items with a Third Item

When the correspondence between sets of non-component debris on two items is high, and the frequency distribution of most of the types of particles is about the same on both items (i.e., the ratios of the types of particles to one another are about the same), it may be that the particles were transferred from a third item that the first two were in contact with. This is illustrated in Case Example 7.

If the frequency distributions of particles on the two items do not differ, standards from potential sources of the particles should be examined before conclusions are reached. In most cases, the debris on an item includes particles of the substrate itself. This depends upon the nature of the substrate; substrate particles are sometimes few, so that even fewer transfer and persist. In the rare case that neither item sheds much and no transfer of particles of substrate is observed, when the ratio of particle types to each other is about the same it may not be possible to distinguish between mutual contact between the items being studied and contact with a third item. However, in most cases transfers of debris from one item onto another include some particles of the substrate. If particles of the item itself are observed in its own debris but not on otherwise similar debris on the other item, the debris may have been transferred to both items from a third source.

Lastly, in most cases where two items are not in contact with each other but are in contact with a third item, each of the first two items will bear debris not found on the other of the two. However there are items which are relatively clean of debris, and it may happen that two such items are in contact with a third item that is rich in debris, and would transfer that debris to both relatively clean items. There would then be insufficient original debris on the two items that were not in contact to suggest that those two items had separate histories. It would only be the unusually similar frequency distributions that might give the analyst pause. It is very difficult under the rather unusual conditions described to establish conclusively that transfer from a third source occurred to the exclusion of mutual contact between the two sources being studied. However, it may be of value to consider the possibility.

When Correspondence of Substrate Particles May Be Coincidental

Sometimes when two items are being evaluated for contact, there is a coincidental correspondence of particles or fibers like the substrate materials; this may appear to be two-way transfer but is not. If transferred particles like the substrate of each item are observed and are numerous, but non-component debris on both items is very different, the correspondence of the former is probably coincidental. The transfer probably occurred between each of the items being evaluated, and another item, not available for examination, which has a substrate like that of the opposite number of each item being evaluated for contact. This possibility should not be dismissed simply because it would be a rare event. Although a specific low probability event, by definition, occurs rarely, low probability events as a whole occur surprisingly often.

When There May Be Loss of Debris Since Contact

If two items that had been in contact both subsequently shed most of the debris from that particular transfer, it is likely that most of the particles like the substrate of the other item would have been shed as well, not only the non-component debris particles. The situation is a little different if one of the items were subsequently used and the other was not, as there could be gain and loss of debris on the one that was used but not on the other item. This could result in dissimilar sets of non-component debris on the two items, with the debris on only one item (the one that was not used or not used much) including particles like the substrate of the other. In this case, the dissimilarity could be attributed to the passage of time, and one could not exclude contact.

Nature and Strength of Association or Exclusion

Decisions about the strength of an association or an exclusion based upon comparisons of non-component debris particles can be made by reference to the same criteria as those used to decide whether or not a conclusion can be reached. As mentioned earlier, when all the conditions for establishing contact are met—essentially a two-way transfer of unique or nearly unique sets of particles—the evidence of corresponding sets of debris can constitute proof of contact, or of having been in a certain location. In other words, one could arrive at the opinion that two objects were in contact.

Conditions for Reaching Qualified Conclusions Supporting Contact

Qualified conclusions supporting contact could be made in the following circumstances: a) if there is a high degree of correspondence between two sets of particles, but there are not that many types of particles in one of the sets; b) if there is a high degree of correspondence between two sets of particles, enough particles and enough types of particles, but many of the particle types are so common that there is a reasonable chance of their being there coincidentally; and c) if there is a high degree of correspondence between two sets of particles and there are enough types of particles, but not many particles of each type. Under each of circumstances a, b, or c, a strong association can be made. It is of course a prerequisite for strong association that particles like the substrate of each item are included in the debris, unless the shedding capacity of each substrate can be shown to be virtually nil.

Conditions for Establishing a Strong Association

When there is a lesser degree of correspondence than required for establishing contact—A strong association could be made if potential original sources for predominant debris particles were found and if the following condition is met: that there are enough particles and enough types of particles, but a lesser degree of correspondence than required for establishing contact. The association would usually be made between the persons involved, between the persons and locations, or between the persons and events rather than between the items themselves. For example, two individuals who are exposed to the same debris-producing processes in a work place or even on the street should have that debris in common, but not the debris from their homes, for instance.

When There Are Differences in Particle Identity but the Particles Could Have Been Produced by the Same Processes

A strong association can be made if two sets of debris exhibit both correspondences and apparent non-correspondences, but the particles that are different could have been produced by the same processes. For example, the environmental debris of a carpenter may include wood shavings of several different types, but the types of wood may vary depending on the work currently in the shop. If the other subsets of debris exhibit a high degree of correspondence, the subset of debris representing the shop can be interpreted with respect to process.

Raising Doubts about Contact

Difficulties in Meeting Conditions for Exclusion—Making definitive exclusions based upon comparisons of debris is inherently more difficult than making definitive associations, even when all the conditions for excluding contact have been met. When no corresponding particles are observed, it is important to really look for them; if corresponding particles are still not found, it is only then that one can consider exclusion. In contrast, if a high degree of correspondence is found between several samples of debris from each of two items, one can reach a conclusion even though one has not sampled every area of the items in question.

Conditions for Strong Doubt about Contact—When two items being compared were collected soon after the event that would have produced transfer, and there are either no corresponding particles or correspondences only among very commonly found particle types but not the others, one can usually exclude the possibility of contact. If samples were taken soon after the event and there are a few corresponding types of particles, but many that do not correspond, the probability of contact is small; one can probably exclude an intense direct contact, but not other types of association.

When Contact Cannot Be Definitively Excluded—When the time frame is not known or is not recent (i.e., the item was not collected soon after the contact being studied), contact cannot be definitively excluded. One can probably exclude contact when the non-component debris is dissimilar, and particles like the substrate of both items being evaluated are among its own debris and also among the debris of the other item, as this implies that each object was in contact with something else that just happened to have the same composition as the other item; however, even then, there is a remote but extant chance that the latter contact was preceded by the contact initially being studied, and that the debris transferred during the first exchange was lost completely. Usually, one can raise doubts as to contact, but cannot actually exclude that possibility. Any conclusion which rests upon an absence of evidence is far more difficult to substantiate than one relying upon a finding of evidence. In evidence examinations involving comparisons of debris, the best way to exclude one hypothesis is to find evidence in support of another. This is illustrated in Case Example 7.

Additional Considerations

Several additional considerations that apply to trace evidence generally must be considered in making decisions about the significance of an association or an exclusion based upon comparisons of debris. Like any historical record, debris must be evaluated in its context, and what applies in one case may not in another; this principle has been discussed by several authors in their respective disciplines (24–28). Several reference points for evaluating the context of trace evidence follow.

Debris as a Forensically Significant Transferred Material

When two objects or beings come into contact, a transfer of material occurs (Locard's Theorem). When a transfer of materials occurs upon contact, the material transferred includes debris. The debris on a person and on the person's clothing reflects that person's habits and environments, as well as any recent albeit non-characteristic particle-producing events. The debris in an environment is characteristic of that environment (5,7,8,10).

Normal Debris Versus Foreign Debris

It is important to determine which particles of debris are from the environments and activities of the wearer of a garment (or the environment of an object), i.e., normal debris, and which particles of debris are foreign. Foreign debris comprises the particles produced by something other than the habitual activities of a person or by something other than the processes that normally take place in an environment. Only clearly foreign material can provide evidence of contact with another object or person. If a particle or fiber that could be from another object or person is found on an item, but is also like a particle or fiber in the normal environmental debris of this item, it is not clearly foreign, and cannot be used as evidence of transfer. For example, if a fiber found on a murder victim is like that of a suspect's sweater, but fibers of that type are also found in the debris of the victim's residence or on the victim's other clothing, not related to the crime, it is not clearly foreign to the deceased.

Debris That Is Characteristic of Object Site Rather Than Object

Debris from the area where an item is found should be examined. When the major part of debris on an item is like the area debris, the item either belongs in that area, or has been there for a significant amount of time. When most of the debris is different than the area debris, the item is either foreign to that area, or has been contaminated by transient human activity (for example, a person passing through an area might spread out food and clothing on some rocks after brushing off the original dust and plant parts). When the area where an item is found is not itself of interest, the area debris standard is used as an elimination sample.

Debris Attributable to Contamination

The possibility of contamination should be evaluated. The very process of packaging evidence and opening it for examination can cause particles to rise and be redeposited (29); this can be evaluated by examining samples of dust from the work area. More troublesome is contamination during transport or storage, for example, if items from a scene are placed unprotected in the trunk of a police car on one day, and clothing from a suspect is placed unprotected in the same trunk several days later. Contamination is usually more problematic when single particle types are being considered, but should not be forgotten as a source of stray fibers in sets of debris, or even as a source of an entire subset of debris. It should go without saying that poor evidence collection procedures that may result in contamination should be vigorously addressed by training and laboratory policy. However, one is sometimes called upon to examine old cases, or cases in which one is not working with the agency that collected it, as in defense work. The only way that one could provide information in such cases is to evaluate any contamination in whatever manner is best suited to the evidence at hand.

Information from Manner of Deposit

The manner of deposit must be evaluated. If fibers like that of the suspect's sweater are found on the jagged edge of a window broken in entry, the deposit is clearly fixed in time and place to actions during or after the breaking of the window. Alternative sources for the deposit would be any other fiber sources that could have had contact with the broken window. If the edges of the fibers are firmly attached to the broken edge and are sharply cut, they were probably deposited while the glass was being broken.

Particles deposited in wet paint or blood or that are an integral part of a smear were deposited in a narrow window of time. In contrast, soil that is deeply ground into the threads of a fabric together with grease and dirt is unlikely to be of only recent origin, and would usually have little value in interpreting recent events, other than as a potential source of transferred particles.

Time Frame of Transfer

The time frame of transfer must be evaluated. Absolute time is not that important unless biological decay or labile chemicals are involved. The important thing is to have some idea of how much the adhering debris could have been altered by events subsequent to the deposit of interest (27). The two principal changes that occur to a deposit of debris are loss of the original particles and fibrous materials, and the addition of other material. Differences between two sets of debris that may permit an exclusion in the case of items recovered shortly after contact might not permit an exclusion after the passage of time. Similarly, as discussed above, a deposit which is directly associated with a specific time can be interpreted even after the passage of much time and subsequent activity.

Location of Debris Particles and Mechanisms of Transfer

The location of the particles should be evaluated, and can provide information about the transfer mechanism and sequence, thus assisting with reconstruction of events, and in some cases assisting in a determination of primary versus secondary or tertiary transfer. If the mechanism hypothesized for the transfer does not account for the location of the particles, the hypothesis may be incorrect, the deposit may be from another event, or in the case of particles loosely adhering to clothing, the particles may have migrated somewhat. The "shakedown" method of collecting debris samples by shaking off debris then scraping clothing with a spatula clearly does not permit such an evaluation.

Relative Proportions of Particles in Debris

The relative proportions of types of particles should be evaluated, and can assist in characterizing a sample. This principle has been especially well demonstrated for soil comparison (30–32), and is generally applicable.

Evaluating Indirect Transfer vis-a-vis Contact

Indirect transfer occurs when material from one object is transferred as debris to a second object, then is transferred from the second object to a third object, and perhaps to a fourth, and so on. This is referred to as secondary, tertiary, and higher degrees of transfer. Recent indirect transfer must be evaluated to determine whether two items were in contact with each other, or whether each was in contact with a third item. The case of particles appearing in about the same proportions on two different items has been discussed as suggesting contact of each with a third item. It is when there is a greater proportion of one set of debris on an item than another set, with the ratio reversed on the second item, that the debris could provide evidence of contact between the two items themselves.[2] This is an example of mutual or two-way transfer: material from one object deposited onto the second object, and material from the second object deposited onto the first.

The proportional mutual transfer of non-component debris can further be used to evaluate whether the transfer of debris formed from substrate materials is direct or indirect, that is, primary transfer versus secondary or tertiary and so on. If a set of debris has been transferred from the clothing of a certain woman to that of a certain man, for example, the frequency of distribution of particles of the transferred debris will usually be noticeably less on the man's clothing than the frequency of distribution of particles produced in the environments of the man himself. If the man then comes into contact with a child, the debris transferred from the man to the child will include the sets of debris produced in his own environments, as well as the set of debris transferred to the man from the woman. Since the latter set of debris is smaller on the man's clothing than

[2] In a secondary transfer experiment reported by Grieve and Biermann (17), a cardigan was worn awhile over a shirt, resulting in a transfer of cardigan fibers; after the cardigan was removed, a pullover was worn over the shirt. Of the debris fibers originally transferred to the shirt from the cardigan, 24.5% transferred to the pullover.

the sets of his own debris, it will usually transfer to the child's clothing in roughly similar proportions. This is illustrated in Case Example 5*c*. It is true that different types of particles are not always shed in the same proportions, may not always transfer in the same proportions, and once transferred, may be lost at different rates (18,33–46). However, in the experience of the author, most though not all of the types of particles in a many-membered set of debris will transfer in roughly similar ratios. This can be tested in individual cases. A few simple experiments may be performed to determine transfer properties on specific items, using the recommendations of Grieve and Biermann (18).

Such considerations based upon ratios of subsets of debris apply under the following conditions: A) when corresponding particles of debris are observed on both items; B) when there is a high degree of correspondence, and C) when the ratios of the subsets of particles can be evaluated. When individual particle types or particles on one item only are being considered, or when there are many types of non-corresponding particles as well, it would rarely be possible to distinguish between secondary (or tertiary, etc.) transfer and transfer due to a contact that is light or of short duration.

Alternative Sources and Significance of Transferred Debris

Alternative sources of transfer must be evaluated (47, p. 18). If evidence of two-way transfer and indirect transfer is absent or sparse, the significance of a matching particle or combination of particles depends upon how common or rare it is (7,14,28,47), and upon how it is adhering to the substrate (14,28,47). When it is rare, there are few possible sources other than the one under study. When it is common, there are many alternative sources. However, the significance increases when the particles can be treated as a set; a many-membered set of even common particles will usually have few possible sources, and may even be unique (7,8).[3] Similarly, the significance of a deposit, such as particles embedded in a damaged area of a weapon, increases if it can be associated with a specific event.

Nature of Material Deposited and Manner of Particle Formation

In considering alternative sources, not only the manner of deposit, but also the nature of the material deposited and the manner in which the particles were formed must be evaluated. For example, a many-membered set of soil particles from a dry and windy plain may be commonly found in a wide geographical area, with variation within a few feet as great as that over several miles, whereas common household dust or city soil in an industrialized country or region is likely to be unique to that house or city yard. Household possessions in industrialized economies, as well as building materials and finishes, typically include so great a variety of manufactured products that no two households would be likely to have the same assemblage of materials. Many different types of particles are produced from these objects, yet each type has a fairly uniform composition. This lends itself well to individualization. It would be useful to know if household debris from regions where many goods are made by hand from commonly available materials can be as readily classified into large numbers of sub-sets. One might encounter fewer types of materials, but with each type exhibiting more varied composition. The author is not aware of any data on this subject.

Investigative Information from Debris

Debris can often provide information about a suspect or about events, or about a sequence of events, assisting in reconstruction, even if there is no corresponding sample for comparison. If the source of debris on some clothing can be characterized, and the type of processes or the location in which they took place can be described, some sites can be eliminated as the source and others suggested, even in the absence of a comparison sample (1–4,6,10).

Using All the Available Evidence, Not Debris Alone

Where no significant corresponding debris is found where it would be expected had contact occurred, and where it is likely but not certain that the conditions for excluding contact have been met, it is important to ensure that all the available evidence be used to reconstruct what actually transpired. This should include not only debris evidence, but also evidence from patterns, staining, abrasion, and other damage. The information thus developed can be used to test the statements made by witnesses and suspects and the working assumptions of investigators, and may also permit the analyst to evaluate better the absence of corresponding debris.

Relevance to Events under Investigation

The relevance of the debris-bearing items to the events under investigation must be established. It matters little if a high degree of correspondence is established between two items that are not related to the event under investigation. The correspondence may arise from other events, and is not itself a proof of relevance. D. A. Stoney has proposed that there is an invariable set of items that are associated with a crime, whose relevance does not depend upon the suspect, that there is also a set of items associated with a suspect, and that associative evidence arises from a correspondence between specific "crime objects" and "suspect objects" (50). Although this has been superseded by a Bayesian analysis (47), it is still useful to consider the original idea.

Understanding the Nature of an Association or Exclusion Established or Suggested by Debris

It is important to understand clearly which questions can be answered by findings of corresponding debris or lack thereof (51,52). Does the evidence suggest that two persons were in contact, or that two items were in contact? Can it be established that a victim was in the trunk of a particular car, or only that the clothing was? Data from additional observations, such as patterns of debris deposits on clothing, may be required to determine if someone was wearing the clothing when it was in contact with other items.

Types of Debris Samples and Requirements of Sampling

Appropriate and adequate samples are necessary to reaching valid conclusions from examinations of debris. Samples of debris from the sites relevant to the event under investigation must be available, as well as debris standards from the usual environments of the people involved. Debris standards should be as routinely collected as carpet, fiber, paint, and soil standards: from the scene of the crime, from any vehicles involved, from other places the participants may have gone during or just prior to the event under investigation, and from the residences of the victims and suspects.

[3] A unique set of particles can, and usually does, comprise particles and fibers which are not themselves unique or even unusual. The traditional concepts of class characteristics and individualizing characteristics cannot be readily applied. In an example from firearms, John Thornton discusses "ensembles" of class characteristics which "tend toward individualization" (48). The concept of uniqueness is discussed by Tuthill (49).

The samples must adequately represent the whole, and must be large enough to permit a determination of which particles are characteristic of the set (53). In establishing which particles constitute the debris normal to a person or environment, a few stray particles or fibers may not be relevant, as they may be from another source; as such, they should be disregarded as part of the debris standard.

It bears repeating that stray fibers can also be deposited while the collected item is in transit, while it is being packaged for evidence storage, or even during examination in the laboratory. While striving to minimize such occurrences, the analyst can test for them by examining particles deposited on other surfaces that would have been exposed at the same time, such as the outer surfaces of packaging, and in the laboratory, of microscope slides left exposed in the examination area when the evidence is first opened.[4]

Methods of Examination

Any discussion of comparisons of debris that result in correspondence between the debris on different items presupposes identification and characterization of the individual fibers and particles which the debris comprises. Identification depends upon the attributes used to distinguish between different, even if closely related, classes of materials, and characterization depends upon the attributes used to distinguish between different members of the same class. Examples of the latter include the relative amount of delustering pigment in a fiber, the degree of weathering of a paint chip, or damage that results from unique events. There are also attributes resulting from classes of processes such as abrasion, fading, weathering, wear produced by repeated individual events of the same types, and conditions of growth and manufacturing; the type of process can be identified and the individual particles characterized.

Clothing encountered in casework often exhibits between 35 to 50 types of debris particles and fibers other than stray particles, not including soil grains, with five or more examples of each type found even in small hand-collected samples of the parent set. These numbers derive from the experience of the author in performance and peer review of casework, and are given as examples, not as a minimum number required to establish contact. The experimental results of Grieve and Biermann demonstrated that fibers of a single type transferred from source garments to shirts worn beneath could number in the thousands (18). "Stray" particles and fibers are those that appear singly or as a very small number; they are not considered part of the sets of debris that characterize the item being examined. There can be as many types of the former as of the latter, but individual stray particles of a single type are few in number.

The validity of correspondence between the individual components in many-membered sets of debris rests upon adequate criteria for determining what constitutes correspondence. An extensive discussion of such criteria is beyond the scope of this paper. However it should be noted that when many-membered sets of debris such as the aforementioned clothing debris are being examined, it is not usually necessary to perform as many levels of testing as it would be if only a small number of debris types were being studied.

The microscope is the instrument best suited to comparisons of many-membered sets of particles, as well as to identification and characterization of the constituent particles themselves (6). While it is often useful to obtain data from other types of examinations on selected particles, the microscope has the advantage of permitting simultaneous separation and analysis of a large number of particles and types of particles, as well as the opportunity to re-examine the very same particles.

An initial visual examination of the item itself should be followed by a stereomicroscopic examination of stains, deposits, and any worn, discolored or otherwise damaged areas of the substrate material. The stereomicroscopic examination permits a preliminary assessment of the nature and manner of deposit of adhering debris. In most cases involving transfers of fibrous and particulate materials, the debris-bearing items are *not* good candidates for comparisons of sets of debris in a way that would allow the criteria for contact and exclusion to be met or approached; Criterion 2D in particular (that the correspondences significantly outweigh the non-correspondences) is rarely met. Therefore, it is important to determine at the outset whether such comparisons should be attempted.

With practices for preventing contamination between items from different sources in place, a sampling of adhering particles and fibers can be obtained using clear sticky tape, and immediately examined using a stereomicroscope. A promising set of samples can then be scanned in situ with a high magnification polarized light microscope. This should be considered part of the sampling process rather than a separate step. The examiner can quickly determine whether or not samples of debris from different items appear to have numerous particles in common, or have remarkably little in common, and decide whether to sample primarily for sets of debris, or to sample instead for certain types of fibers or particles which may be from a target source.

Additional particles hand-picked from the item itself can then be selected and mounted for transmitted light microscopy directly into a receiving liquid, preferably an appropriate refractive index oil,[5] or can be mounted dry for reflected light microscopy. It is convenient to sort immediately the particles by color or size or another property that will permit easy tabulation of individual analyses. Identification and characterization of each particle type can readily be accomplished by polarized light microscopy, in most cases without removing the particle from the original mounting medium. Even the samples on clear sticky tape can be examined in situ if the sticky tape, selected for minimal birefringence, is placed onto a drop of refractive index oil on a microscope slide then covered with another drop of oil and a cover slip; although precise refractive index and retardation measurements cannot be obtained this way, accurate relative measurements can be.

Sufficient analytical information should be recorded so that the tabulated lists can be compared (10); these would typically include size, morphological properties including shape deduced from optical section (or crystal habit), and optical properties such as color, birefringence, dichroism or pleochroism, and refractive index relative to the mounting medium. Approximate frequency should also be noted, for sticky tape as well as mounted samples, as there may be a significant bias introduced by the method of sample collection. Individual mounted particles should be clearly enough separated on the slide so that after the initial analyses, particles can be selected for direct comparisons, and if desirable, additional testing.

In the case of opaque particles, a partial identification and a good characterization can often be accomplished using reflected light microscopy. Analysis of organic components or methods for ele-

[4] One can leave slides out for the duration of examinations or for given intervals of time, with a drop of refractive index oil on the slide to receive and hold the particles.

[5] For fibers, for example, Fong suggests using $n = 1.525$ oil, as most fibers can thus be classified without remounting (54); Graves suggests $n = 1.540$ for soil (32); Petraco and DeForest favor $n = 1.539$ for dust in general (10). See also Cook and Norton (55), and Roe, Cook and North (56).

mental analysis (whether microchemical or instrumental) must often be used as well. Techniques for dry mounting should be chosen so as not to cause contamination problems in subsequent testing. For example, samples to be further tested via infrared spectroscopy or a method for elemental analysis should not be mounted in a material such as clay which cannot be readily dissolved away.

In selecting analytical methods, it is the opinion of the author that some of the considerations that apply to smaller sets of debris, or to comparisons of component particles, may not apply to comparisons of many-membered sets of debris. Other scientists believe that the same testing criteria should be applied in both cases. In deciding between these points of view, one might consider that if transfer of only the component materials is being studied, an incorrect result in comparing a single type of particle would lead to an incorrect conclusion regarding contact. However a similar error with a single type of non-component debris particle in a many-membered set of debris would have little impact on the overall conclusion; this can be demonstrated using Bayes' Theorem and the likelihood ratio.

Moreover, errors in interpretation of transfers of trace evidence may arise when testing is confined to target particles and a few types of debris particles. The possibility of such an error was the basis of a Royal Commission report in Australia, where reliance upon transfer evidence with insufficient regard for distinguishing foreign from normal debris was feared to have resulted in a miscarriage of justice (57).[6] Even when the criteria for contact or exclusion cannot be met, and even if a complete battery of tests is not performed on each type of particle, context-based examinations of debris and comparisons of transferred non-component debris can be important in preventing such errors. The impact of information lost when comparisons of debris are not performed, and of errors of association that may result—errors of both incorrect association and incorrect type of association—may be far greater than the impact of a small number of incorrect comparison results of individual non-component debris fibers.

In the opinion of the author, if non-component colored synthetic fibers from two many-membered sets of debris exhibit the same morphological and optical properties, it would not in most cases be necessary to perform further testing on the fiber dyes. If non-component paint chips were found to correspond using infrared spectroscopy, it might not be necessary to perform elemental analysis as well. One might, however, wish to identify and characterize further a sample of the fibers or particles that correspond with the component materials of the other item. The correct identity of each type of debris particle that corresponds with a component material of one of the items being studied is far more significant to conclusions about transfer of debris than is the identity of any single type of non-component particle or fiber. More extensive testing may therefore be required of the former than of the latter.

Similarly, in most cases involving transfer evidence it is good practice to perform intercomparisons of all significant debris particles with reference to standards from potential original sources (45). However in comparing many-membered sets of debris when all the criteria for establishing contact have been met, it is the identity and character of the debris itself that provides the basis for conclusions, not the comparison of each individual particle that the debris comprises. As discussed earlier (Additional Considerations, standards of debris should be employed to obviate problems of interpretation just as standards of component materials would be used in other types of cases, and particles that may be component materials transferred from one of the items being studied should be compared with a standard of that item.

Computer software that permits listing and sorting by category can be very useful in tabulating and comparing data of particles and fibers from different items. It is not a prerequisite for comparisons of many-membered sets of debris—computer tabulation was not used in most of the case examples in this paper. However, hand-tabulated lists permit the data to be sorted by at most two criteria at a time, whereas appropriate software permits ready sorting by as many criteria as are listed. This permits the scientist to view patterns in the data that might otherwise have been missed, and allows the laboratory to compile frequency of occurrence data.

It should be noted that this methodology was developed in actual casework performed in two busy crime laboratories, and is designed to permit such work to actually be performed. The initial sample assessment restricts this time-consuming approach to cases in which there is a reasonable chance of a successful outcome. Organized sample mounting reduces the amount of time spent searching for individual particles. The emphasis on microscopy permits most fibers and particles to be examined with a minimum of additional sample preparation. The information value justifies the time spent.

Some Case Examples from Actual Cases

Case Example 1

All conditions for establishing and excluding contact met; Items collected soon after the event under investigation

A police officer shot and killed a driver whom he had stopped for speeding, claiming that the speeder had threatened him with a penknife; a penknife was found in the deceased driver's hand. Debris in the blade well of the knife was compared with debris from the pockets of the deceased, but the knife debris did not include the tobacco and food particles nor the paint and fiber types found in the pockets of the deceased. However, it did correspond with debris from the pockets of the officer's uniform, upwards of 35 different types of particles. As this was considered a unique set of debris, the high degree of correspondence proved that the knife had been carried in the officer's pocket. Since there was no evidence that the knife had been wrested from the officer nor indeed of any struggle at all, the knife must have been carried by the officer then placed in the hand of the driver.[7]

Case Example 2

Inconclusive regarding contact, as the correspondences did not significantly outweigh non-correspondences; Indirect association suggested

A man and a woman were killed after having hot objects applied to their persons, burning their skin and melting areas of their clothing; their bodies were transported and found in a field outside the city. Debris from their clothing included fur fibers, as well as other debris unlike samples from their residence. Police developed a suspect who had just moved out of his apartment, leaving behind only debris. Many of the debris particles corresponded with foreign debris on the victims, but the correspondence was far from complete, with missing and extra particle types; this neither proved nor dis-

[6] To the credit of the Australian courts, the commission investigated, and recommended that the prisoner be freed without a re-trial.

[7] This occurred in Detroit, Michigan in 1972; the officer was accused of murder, tried, and acquitted.

proved that the victims had been at that site, but did hint at some connection.

All conditions met for establishing contact; Unique set of debris

Samples later obtained from a room in the basement of the suspect's work place—used as a fur storage vault by the previous tenant, a dry-cleaning establishment—exhibited a high degree of correspondence with the foreign debris off the victims, with nearly 40 fiber types and eleven types of fur; all but three fiber types were found in both samples. This was considered a unique set of debris, establishing that the man and woman had been in that room within a short time of the homicide.

Conditions for establishing contact only partly met: Fewer types of particles than required were found as well as several additional particle types, but the nature of deposit of some fibers similar to standards of substrate fabrics was specifically linked to events under investigation

Similar debris was also found in the trunk of the suspect's car, but there were fewer particle types in the car, as well as several additional types of particles not found on the clothing, allowing a qualified association only when debris alone was considered. However, corresponding human hairs and traces of blood were found as well, and a padded glove found in the trunk exhibited deposits of heat-damaged fibers like heat-damaged fibers in burnt areas of the clothing of the victims, thus permitting a strong association with the events.

Case Example 3

Conditions for establishing contact not met: Degree of correspondence not high, but correspondence of several types of particles with standards of potential original sources permitted a strong association

A woman was killed and her body found outside a 400-unit apartment building, and a bloody blanket was found in the apartment dumpster. A man who had lived in the building became a suspect after coming to police attention for trying to set a fire in the dumpster. Despite the absence of fibers like the substrate of the victim's smooth knit dress on the blanket, fibers like the blanket substrate were found on the dress, and there was a high degree of correspondence between the non-component debris on her clothing and on the bloody blanket. However, any association with the man's apartment was as yet unproven. The man had moved out shortly afterwards, selling all his furniture in a "garage" sale; the building manager cleaned the apartment then rented it to someone else. However, after finding blood soaked into the wood beneath the carpet, police collected samples of the debris still found in the corners of the newly rented apartment. The blood could not be grouped, nor could species be determined; the apartment debris exhibited some correspondence with debris off the victim's clothing and the blanket, but the correspondence was not high. Police then visited each unit in the apartment, and obtained samples of fabric items purchased in the garage sale; standards from these items were compared directly with debris off the victim and off the blanket, resulting in correspondence with several predominant fiber types. This suggested a strong association. The apartment was firmly established as the site of the murder later, when the bloodstains under the carpet were found to have a pattern of denser and lighter areas corresponding to those of the bloodstain pattern on the blanket; as the blanket had been linked to the victim by means of corresponding debris, this constituted proof.

Case Example 4

Conditions for establishing contact only partly met: High degree of correspondence, but few particles and few types of particles

Two little boys reported being sodomized in a motel, and police quickly arrested the man who had rented the room. The boys' undershorts as well as the clothing of the suspect were in evidence, but not the boys' outer clothing, and when biochemical testing proved inconclusive, it was too late to get the boys' pants and shorts for examination of trace evidence, as they had been wearing the clothing in the intervening weeks, and their mother was uncertain which pants they wore the day of the crime. However, there were a few debris fibers on their undershorts comprising five types of fibers; these fibers corresponded with the common substrate fiber of the man's pants and with four of the other five types of debris fibers on the man's shorts. The correspondence between the two sets of debris was high, but the few particles and small number of particle types permitted a qualified conclusion only.

Case Example 5

All conditions for establishing contact met: Unique sets of debris

A woman was raped and killed on her bed; the man in the apartment upstairs was suspected of the crime. Results of biochemical testing on vaginal samples were not very specific and since she died by strangulation, there was little bloodshed. Examinations of debris became critical to the case. The suspect had been in the apartment several times before, so only the items specifically associated with the crime (the victim's nightgown, socks used as bindings, and debris off her body and bed) were examined for possible transfers of debris; apartment debris standards were used to establish normal versus foreign debris. There was a high degree of correspondence between the over 40 types of foreign debris on the victim and the debris on the suspect's sweatshirt, including fibers, tobacco particles, hair from several people and soil; in addition, the foreign debris on the sweatshirt corresponded well with debris and substrate fibers of the bindings and debris on the victim. These were considered unique sets of debris, ruling out alternative hypotheses.

Conditions for establishing contact met; Sufficient though few particles and particle types; Deposit fixed in time

A pill of fibers found on the buttocks of the deceased was of the same type as pilling found on the inner thighs of the suspect's pants. Both questioned and known fiber pills comprised damaged polyester fibers like those in the polyester/cotton blend pants, and also several other types of fibers and cat or dog fur hair. Although the number of particles was few, it was enough to be significant because the area where it was deposited was clean of other particles, and would not long have retained debris. The number of particle types was also small, but their deposit as a "pill" and the inclusion of damaged fibers considerably reduced the number of possible sources. While it may not have been unique, the "pill" was highly significant evidence of contact.

Mutual proportional transfer suggesting secondary transfer of a subset of the debris, substantiated by observing similar proportions on the item of primary transfer; Significance of hair transfer evaluated in the context of debris associated with the same person

Some of the hair on the victim was similar to hair standards from the suspect's spouse; hairs of that type were also found on the suspect's sweatshirt. Such hairs were found on items of both the victim and the suspect, but were fewer in number than hairs similar to the suspect's own, and on items from both suspect and victim were found in the same approximate proportions to the suspect's hairs. In order to further evaluate the transfer of hairs, the transfer of debris was studied. Samples of fiber sources had been obtained from the couple's upstairs apartment, and among the foreign fibers and other particles found on the victim, those like the fiber sources associated with the spouse alone were much fewer in number than those like either the suspect's fabric items or items used in common; moreover, they were deposited on the crime objects in about the same proportion to debris associated with the suspect as were deposits on the suspect's sweatshirt. A strong association was made with the suspect, and his spouse was not implicated.

Case Example 6

All conditions met for establishing contact; Microscopy was supplemented by infrared spectroscopy

A young woman was killed by strangulation in a rural area and not much blood was shed; her clothes were found at a distance from her body. Strong associations were made between debris on her body, debris on her clothing, and debris in a workshop in one of the outbuildings of a farm to which only the suspect had access at that time. Significant among the debris particles were at least seven types of red paint chips and at least four types of white paint chips. Most of the paints were not distinguishable using reflected light microscopy alone, as they were common single-layer house and tool paints, but were readily distinguished by infrared spectroscopy.

Case Example 7

Conditions for excluding contact not met, but proportions of debris raise questions; Debris used in reconstruction of events

Evidence in a murder in a rural area was being examined to aid in reconstruction of events; it was thought that the victim was stabbed through a blanket, as no blood spatter was evident and there were suggestions that another item may have covered his clothing. A blanket with a few bloodstains and several stab slits was confiscated from a suspect. Results of biochemical testing of the blood were unclear, but there was a rich sample of debris on the blanket which exhibited a high degree of correspondence with debris on the victim's clothes, and with debris in a barn to which the suspect had access. Yet, because the proportions of debris on the clothing and on the blanket were about the same, there was nothing to exclude the possibility that the debris was from the barn itself, and that both the victim and the man with the blanket could each have been there at a different time. The absence of fibers like the clothing of the victim was not a factor, as his clothing did not shed much.

The suspect claimed that he had rested there after cutting himself, and that he sat on the blanket bleeding a little while dressing the cut; he recounted absently stabbing the blanket with the offending knife. While not specifically supporting this account, the evidence did not refute it either. Another suspect was later developed by the police, a man who also had access to the barn. He was linked to the murder via biochemical testing and blood spatter on his clothing, as well as debris.

This case example illustrates the difficulty of clearing someone of suspicion simply by a lack of evidence; it was only when another suspect was developed and associations with the second suspect established through physical evidence that the first man was cleared of suspicion. However, questions raised by the examinations of debris as to whether the suspicion was justified gave the police an impetus to continue the investigation.

Case Example 8

All conditions for establishing contact met; Debris was used in reconstruction of events; Condition of hairs directly related to events under investigation

A man was killed in a house by a blow to the head after some of his hair had been cut off and thrown into a fireplace; his warm body was found several miles away in the woods. He was thought to have been transported in a pickup truck carrying pressed-fiber logs, as there were little piles of sawdust in the road between the house and the body. There was also a blanket found on the road about a mile from the body, and another blanket found near the house.

The foreign debris on the victim's clothing was a rich collection of particle types, including fibers, sawdust, wood chips, plant parts, paint of several colors, soil, animal hair of several types, and human hair from several individuals; it exhibited a high degree of correspondence with the debris on one side of the blanket found about a mile down the road; correspondence with debris on the other side of the blanket was partial only, the latter in turn exhibiting a high degree of correspondence with one side of that blanket which was nearer the house. The other side of the latter corresponded well with samples of debris from the floor of the house, including some burnt ashes and cut singed hairs similar to the victim's. The high degree of correspondence between the debris samples allowed contact to be established among a series of items, based upon unique sets of transferred debris.

Probability of being there without correspondence would be high, except that the location and manner of deposit narrow the alternative possibilities

The type of sawdust found in the road and in the pickup truck was found on all the other items as well. Because the crime occurred in logging country, this was a common particle type; the sawdust in the pickup was not given much weight in reaching conclusions regarding transfers of debris to the clothing. However, the sawdust on the road was found in little piles, and the piles were found only on the section of road between the body site and the general area of the house. It was thus significant in linking the two locations.

Case Example 9

All conditions met for excluding association based upon information provided by debris

A pedestrian was struck and killed, with make, model and year of an older model car determined by metallic green paint chips and pieces of plastic headlight cover found on and by the body. Incredibly, four cars of that type with a damaged or newly repaired fender and headlight cover were found in the locality where this occurred. Three of the cars were eliminated by trace evidence, two of them because of paint smears indicating collisions with other vehicles rather than with a pedestrian, and the third via debris: the headlight cover, although not the original, had pollen, leaf, and seed parts spanning three seasons deposited along the rim where the cover fit into the frame, but only two months had elapsed since the accident.

Contact established because of the manner of deposit despite non-distinctive deposits and the passage of time

A fourth vehicle later established as the one that struck the pedestrian was found three months after the collision. There were fabric impressions including fibers embedded in the paint of the dented fender where the paint had been softened, probably by the heat of friction generated by the body sliding over the vehicle; smears of similar paint were found on the victim's blue denim pants. Although the denim fabric and cotton fibers were not very distinctive, the deposit clearly occurred during a vehicle-pedestrian collision. This, together with the paint smears on the pants, reduced to a small number the alternative possibilities so that other investigative information could be used to eliminate them.

Case Example 10

Conditions for establishing contact not met, as the correspondences in particle types did not greatly outweigh the non-correspondences; Association established via non-corresponding particle types reflecting corresponding processes of formation

A woman was found stabbed to death in an alley, and a man who lived in an apartment building nearby was accused of the murder after police found a pair of bloody pants in the apartment dumpster. Biochemical testing established the blood to be consistent with that of the victim. When the man said that the pants were not his, debris from the pockets of the bloody pants as well as debris from three pairs of the defendant's pants were examined at his attorney's request. The debris in each pair of pants consisted of a subset consisting of particles of types also found in the pockets of the other pants, but included as well as significant portion of apparently non-corresponding debris consisting of different types of wood shavings, sawdust, dried droplets and chips of paint, and metal turnings. It was evident that the latter sub-set of debris in each pair of pants, though composed of different particles, was produced by the same particle-forming processes, and suggested occupational sources (the author later found out that the man was a cabinet maker). As such, it provided strong evidence that the bloody pants were in fact from the same person as the other three pairs.

Testing the Proposed Criteria

The concept of probability as a basis for making decisions, and the concept of characteristic sets of debris, together form the basis of the criteria proposed for making decisions about contact, association, and exclusion. In evaluating transfers of sets of debris, probability cannot be straightforwardly calculated because of the complexity of factors affecting the distribution of particles and fibers in any given set and subset. The semi-quantitative approaches proposed for evaluating deposits of a few types of fibers that correspond with known fabric sources (58–65) cannot be readily applied to evaluating corresponding sets of mostly non-component debris. In any case, since sets of debris are by their nature unique or nearly so, the statistical data needed for probability calculations would have to be determined for each individual case. Graphical methods proposed for evaluating complicated patterns of evidence (66), while useful to probability calculations by virtue of analysis of dependencies among variables, do not account for the iterative nature of transfers of sets of debris. A collection of debris results from repetitive particle-producing processes; moreover, sets of debris produced in environments related via a common agent are repeatedly exchanged, continually modifying the debris of each environment. These are iterative processes.[8] Interpretation of mostly non-iterative one-time transfer to an unrelated object must rely upon understanding the iterative transfers which preceded it.

Despite these limitations, probability can be qualitatively estimated through the application of Bayes' Rule. For a more rigorous development of Bayes' Rule (67,68) and its applications to forensic science (45,47,69–75), the reader is referred elsewhere. This discussion is restricted to the use of Bayes' Rule in testing the criteria proposed in this paper.[9]

Bayes' Rule

Bayes' Rule relates sets of observations and measurements, for example, the data of a paint comparison, to proposed sets of conditions or events, such as the hypothesis that a certain car struck a certain person. Bayes' Rule expresses the probability that a certain event has occurred given a specific condition or conditions of measurement. For example, it can be used to derive the probability that two garments were in contact with each other, given the condition that fibers like those that each garment comprises were found on the opposite item. As a model it is broadly applicable to evaluating scientific endeavors, and is of particular interest in comparing a hypothesis with an alternative hypothesis in light of a particular analytical result(s). In the aforementioned example, one alternative hypothesis might be that despite corresponding fibers the garments were not in contact, but that the fibers on both items were transferred from a third source that at one time had been in contact with both garments. Another hypothesis might be that there were two separate unrelated sources for the corresponding fibers.

Where J is the event and I is the condition, Bayes' Rule—written in terms of odds rather than probability, is:

$$O(J \mid I) = O(J) \cdot \frac{[P(I \mid J)]}{[P(I \mid \text{not}-J)]},$$

where $O(J \mid I)$ is the odds of event J occurring given the condition I; $O(J)$ is the odds of event J occurring; $P(I \mid J)$ is the probability of condition I being present if event J occurs; and $P(I \mid \text{not-}J)$ is the probability of condition I being present if event J does not occur (47, p. 41).

Thus, Bayes' Rule expresses a relationship between the probability of an event given certain facts or data, and the probability of the facts or data given the event. When Bayes' Rule is written in the odds form rather than the probability form, the probabilities of alternative hypotheses (i.e., other events) are incorporated, as is in-

[8] Iteration is feedback. Mathematically, an iterative equation is non-linear, one of a series in which the variable acts upon itself, and the answer to the first calculation is a variable in the second, and so on. For example, $x_{(n+1)} = c\,(x_n)(1 - x_n)$ and $x_{(n+2)} = c\,(x_{n+1})(1 - x_{n+1})$ where c is a constant and x is a variable.

[9] Some authors have proposed applying Bayes' Rule to test the impact of particular evidence upon evaluations of the guilt or innocence of a particular individual. However in this paper, Bayes' Rule is being applied to evaluations of specific interpretations or conclusions about physical occurrences rather than to the moral and philosophical as well as legal question of guilt.

herent in any statement of odds. Both probability and odds express a likelihood of occurrence. Probability P is the number of times that a particular outcome occurs, divided by the number of times all possible outcomes occur. The Odds O of the same occurrence are the number of times a particular outcome occurs, divided by the number of times all other possible outcomes occur ("odds on"); "odds against" is the inverse. That is, $O = P/(1-P)$. If $P = \frac{1}{2}$, O is 1 to 1; if $P = \frac{2}{3}$, O is 2 to 1 "odds on;" if $P = \frac{1}{3}$, O is 2 to 1 against.

Testing the Criteria by Reference to Bayes' Factor

A part of Bayes' Rule, Bayes' Factor, also known as the likelihood ratio, is of special interest to forensic scientists in evaluating the impact of evidence upon a case, or the impact of specific evidence upon a conclusion. Bayes' Factor is the ratio of the probability of a certain condition being present when an event has occurred, to the probability of the same condition being present if the event did not occur. It is the last term in Bayes' Rule as written above:

$$\frac{[P(I \mid J)]}{[P(I \mid \text{not}-J)]}$$

This ratio is a way of expressing the impact of the particular condition upon the overall probability of the event itself, which usually includes other factors. For example, in assessing the odds of the event that two items were in contact, one might evaluate the impact of the condition which is the presence of a particular fiber. If there is a high probability that the fiber would have transferred, persisted and been detected if contact occurred—a high $P(I \mid J)$—but a low probability of its being there if contact had not in fact occurred—a low $P(I \mid \text{not}-J)$—the likelihood ratio would be high, and the presence of the fiber would have a high impact upon the overall probability of contact. On the other hand, if the probability is high of its being there randomly, the likelihood ratio would be close to one, as both $P(I \mid J)$ and $P(I \mid \text{not}-J)$ would be high, and the presence of the fiber would have little or no impact on the overall probability of contact.

Suppose instead that there is a low probability that the fiber would have transferred, persisted and been detected had contact occurred, but a vanishingly low probability of its being there if contact had not in fact occurred. In this case the likelihood ratio would also be high, and the presence of the fiber would thus have a high impact on the overall probability of contact; this is the basis for the strong conclusions possible with even a limited amount of evidence that is fixed in time or by manner of deposit. In Case Example 5, a fiber pill like those found on the inner thighs of a suspect's pants was deposited on the buttocks of a homicide victim; this would seem an unlikely occurrence even if contact with the suspect's pants had occurred; however it is extremely unlikely that this fiber pill would have been there had contact not occurred, much less if someone else had committed the crime.

The likelihood ratio is low (much less than one) when the criteria for exclusion are met; these criteria reflect a high value for $P(I \mid \text{not}-J)$ and a much lower $P(I \mid J)$. In this case, the condition "I" is the absence of particles rather than their presence. When the particles of interest would be expected but are not found, $P(I \mid J)$ is low; when a number of other particles are found instead, $P(I \mid \text{not}-J)$ is high. If there are not many particles altogether, $P(I \mid \text{not}-J)$ cannot be high, therefore the absence of the particles or fibers of interest has a smaller impact, and exclusion may not be possible. Similarly, when the particle of interest does not transfer readily, or would not be expected to persist or be detected once transferred, its absence would not be surprising even if contact had occurred; $P(I \mid J)$ would therefore be low; $P(I \mid \text{not}-J)$ would also be low; the likelihood ratio would be close to one, and the absence of this particle would have little impact upon the conclusion, even if it is a constituent fiber of one of the items being studied for the possibility of contact.

If $P(I \mid J)$ is lowered by there not being enough particles or not enough types of particles, or if $P(I \mid J)$ is lowered with respect to $P(I \mid \text{not}-J)$ when the correspondences do not greatly outweigh the non-correspondences, factors that would increase $P(I \mid J)$ or decrease $P(I \mid \text{not}-J)$ might allow a conclusion to be reached that would otherwise not have been justified. For example, finding potential original sources of predominant debris particles would increase $P(I \mid J)$. Finding particles embedded in dried blood or a crack in a weapon would decrease $P(I \mid \text{not}-J)$, as would other factors which could fix an event in time or otherwise limit its context.

Presenting Conclusions in Court

Almost every testimony of a forensic scientist in a court of law is bounded by two imperatives: to develop fully all the information that has been derived from the examinations conducted, and to express clearly the limitations of the results so that the trier of fact does not attribute more significance to the findings than is warranted. In other words, the analyst should strive to minimize both Type I (incorrect exclusion) and Type II errors (incorrect association or inclusion), not only in arriving at conclusions but also in presenting them.

In using the evidence of corresponding sets of debris in court, especially when the forensic scientist has reached the opinion that two persons or objects were in contact, there are several reasons for caution, foremost of which is that other possibilities are not always anticipated. For example, clothing may be purchased at garage sales or second-hand stores, or may be used by several different people in the same household. A piece of clothing used in a crime might be later used by a person who was not involved; similarly, a second-hand item of clothing used in a crime might exhibit debris that is more characteristic of its original owner than of the perpetrator wearing it. The true history of an item is not always available, and the appropriate samples that might test it are often not accessible. Two clothing items may have been in contact, but not while both were being worn. Additionally, insofar as the author is aware, there have not yet been the published formal studies of transfers of sets of debris which might assist the analyst in interpreting the conclusions.

It is often possible to present the data of the many correspondences of particles, together with information about mechanisms of transfer, without specifically offering an opinion that two items were in contact. One of the best ways to explain how strongly the analytical results either imply contact or cast doubt upon there having been contact between two items is to present the alternative hypotheses which are extremely unlikely in comparison. This is a way of using Bayes' theorem without numbers.

When all the conditions for establishing contact are met, the comparison of sets of debris provides a powerful method of demonstrating this, and if asked whether one has reached an opinion regarding contact, one can proffer it along with appropriate provisos, explaining that the opinion is conditioned upon certain assumptions about the history or use of items that are the source of debris. It is usually not possible to exclude contact, and opinions interpreting a lack of correspondence between items are usually confined to raising doubts. There are rare situations in which an opinion excluding contact is justified, and should be offered.

Further Work

The growing body of published studies pertaining to transfers and occurrence of trace evidence, including transfer of fibers (18,29,34–44) and occurrence of fibers and other particles (18,76–85) does not include studies treating sets of debris. Such studies, under both actual and simulated conditions, would provide experimental data for evaluating the ideas presented in this paper, and would be useful in addressing the following: 1. A) Which types of particulate and fibrous debris are typically found as trace evidence on clothing, their relative frequency, and the mechanisms of their production (there is an existing body of literature on particle production in the fields of materials science and contamination studies that could provide a good start for the forensic trace evidence investigator); B) The mechanisms of formation and resulting composition of sets of site-produced, shed, and aerially transported debris in an environment such as a room, house, or work place; and C) The transfer and persistence of debris on objects exposed to a particular environment; 2. On an item of clothing belonging to and used by one individual, the relative abundance of the debris that comprise particles and fibers characteristic of that person's environments, compared with the relative abundance of particles and fibers from unattributed sources; there is a growing body of work on the population of fibers found on car seats (80–83), public places (85), and outdoor surfaces (84), but not yet on sets of debris; 3. The degree of correspondence of debris from among various articles of clothing from an individual, including second-hand clothing; 4. The degree of correspondence of debris from among articles of clothing from different people living in the same household; and 5. The types and degree of correspondence between debris found on shared clothing compared with the types and degree of correspondence between debris found on non-shared clothing of different people living in the same household.

Summary

Evidence from transfers of debris can be useful in reaching conclusions about associative evidence, and when transfer of non-component particles is also considered, can sometimes constitute proof of contact. Such proof is based upon the correspondence of unique or near-unique sets of particles and fibers rather than upon correspondence of unique or rare particles or fibers themselves. In selecting questioned samples to examine, interpreting the results of examinations and ascribing significance to the conclusions, it is first necessary to establish which debris is foreign and which is normal by examining debris standards from relevant locations, and to consider the properties of the debris, the context of the deposits, and the nature of transfers. With adequate samples, the use of microscopy to analyze particles, appropriate conditions of subsequent comparison and clear thinking about experimental design and results, the examiner can reach conclusions using context-based data analysis relying upon qualitative probabilities and the concept of sets. The criteria for reaching conclusions can be tested by reference to Bayes' Factor (the likelihood ratio). Along with piece matches, fingerprints, toolmarks, and other prints and impressions, and DNA typing of semen from vaginal samples, evidence based upon transfers of debris is one of the few types of evidence that offers the potential of definitive conclusions regarding contact between persons or items, and can be valid, useful, and practical in making this and other associations and exclusions and evaluating their nature.

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Additional information (reprints are not available from the author):
Chesterene Cwiklik
Cwiklik & Associates
2400 6th Avenue South #257
Seattle, WA 98134
email: bi492@scn.org