THE THEORETICAL BASES OF COLLECTIONS MANAGEMENT

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Abstract.—A collection may be managed as individual elements or as a set of elements. Collection management can be depicted graphically with order shown on the x-axis, collection growth on the y-axis, and conservation on the z-axis. Individual collection elements, or the entire set, can be graphed as points in xyz-space. The management of the collection can be evaluated by analyzing the location and form of the cluster of points p (x, y, z). This analysis may be done in conjunction with other methods of collection management evaluation, such as the Collection Health Index. The cost of management of a collection is equivalent to the cost of reducing the expression of entropy in the collection, which is accomplished by controlling the agents of deterioration (direct physical forces; theft; vandalism, displacement and curatorial neglect; fire; water; pests; contaminants and pollutants; light and radiation; incorrect temperature; and incorrect relative humidity). These are easiest to control at the microenvironment level, and microenvironments are best controlled using the principles of the theory of enclosures. Collections should be managed with an understanding of entropy, enclosure theory, and preventive conservation theory to direct the investment of resources.

Resumen.—Los especimenes en una colección son manejados como elementos individuales, pero la colección entera es manejada como un grupo. El manejo de las colecciones puede ser explicado de manera gráfica con orden sobre el eje x, el crecimiento de la colección sobre el eje y, y la conservación de los especímenes sobre el eje z. La ubicación de los elementos individuales (ejemplares) en una gráfica permiten evaluar y predecir el estado en que se encuentra la colección. Mucho del costo del manejo de una colección es equivalente al costo de reducir la expressión de la entropía en la colección y, esto va acompañado del control que se esté realizando sobre los agentes de deterioro de la colección (fuerzas físicas directas, ladrones, vándalos, fuego, agua, pestes, contaminación, radiación, temperaturas y, humedades relativas incorrectas). Los agentes de deterioro están orientados a controlar los niveles del microambiente y, los microambientes se controlan usando los principios de la teoría de envolturas. El control de la tasa de la entropía en el cuidado y manejo de colecciones de historia natural es parte del conservación preventiva. Las colecciones deben ser manejadas con el fin de mantener un equilibrio entre el uso corriente y su preservación para el uso futuro, para ello se deben aplicar las teorías de la entropía, envolturas y, conservación preventiva y de esta manera redireccionar la inversión de los recursos.

The history of preservation is much older than the history of museums. For example, mummies were prepared at least 7,800 years ago in Peru and 5,000 years ago in Egypt (Brier 1998). It is estimated that at present there are approximately 2,500,000,000 natural history specimens and objects (Duckworth et al. 1993) in some 6,500 collections (Mares 1993). Worldwide, the ratio of collection care workers to natural history collection objects averages 1:200,000. However, there are relatively few specimens in natural history museums collected before 1850, and the oldest specimens in collections are often not in a good state of preservation (Hawks 1990). All of the causes of collection deterioration—organic, inorganic, and organizational—are expressions of entropy. Given the quantity and age of the specimens and objects in collections, and the low number of trained

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professionals to care for them, how can collection management resources be best directed to prolong the useful life of collections?

A *collection* is a set of related *elements* (*cf.* Pearce 1992). The elements may be horseshoes or horseshoe crabs, but in all cases, for the set C, with elements (a, b, c, . . . , z), we can state that the elements are members of the set C by use of the symbol $\in$, thus

$$(a, b, c \ldots, z) \in C.$$

The specimens or objects in a collection may be managed as individual elements (a, b, c, . . . , z), but the entire collection is also managed as a set. One of the characteristics of a collection of elements that distinguishes it from other assemblages of elements is that a collection has some sort of order (Pearce 1992). *Entropy* is the quantitative measure of the degree of disorder (lack of order) in a system (Arnheim 1971). Historically, the most fundamental aspect of collection management has been establishing and maintaining order among the elements of the set that comprises the collection, thus reducing entropy. The management of a collection can be depicted graphically, as show in Figure 1A, with the x-axis as the *order axis.* This is the traditional view of collection management—resist an increase in entropy.

The extremes of the order axis are very chaotic situations and very organized situations. In a properly ordered collection, each element has an appropriate physical location within the organizational structure. This physical location is determined by the systematic organization of the collection and the type of specimen or object it is (e.g., a dry specimen, a fluid-preserved specimen, or a frozen tissue sample in a collection that is arranged in alphabetical order by scientific name). The physical location for the element is called a *cell* (R. Waller, pers. comm. 1987). The cell is a particular, special and unique place for the element in the collection. To the extreme left on the order axis (Fig. 1A), the collection is disorganized—there is more than one element per cell, there are elements that are not in their cells, or there are elements in the collection that do not have cells. To the extreme right of the order axis the collection is highly organized, with each element located in its respective cell. The elements to the extreme left are unusable due to their disorder. The elements on the extreme right are unusable due to their order—the elements are in an order that cannot be maintained, an order that is very expensive to maintain, or the use of the elements drastically changes their position on the order axis.

The mid-point on the x-axis is the state in which each element of the collection is in its appropriate cell, in a usable order. Elements to the left of the midpoint show increasing entropy because one or more elements are not in their cells. Elements to the right of the midpoint show decreasing entropy, resulting from some further ordering or organization of the elements in their cells. *Disorder* may be defined simply as the absence of order (Feibleman 1968); while *order* may be defined as ‘‘a similarity among disparate elements’’ (Feibleman 1968:3) or a recognizable pattern. Defined this way, order ‘‘has the limitation that it cannot be total’’ (Feibleman 1968:4). The mid-point of the x-axis is thus set at the point where disorder among elements may be said to end and order among elements be said to begin, as the order axis extends in both directions to infinity.

The second consideration for collection management is the *collection growth*

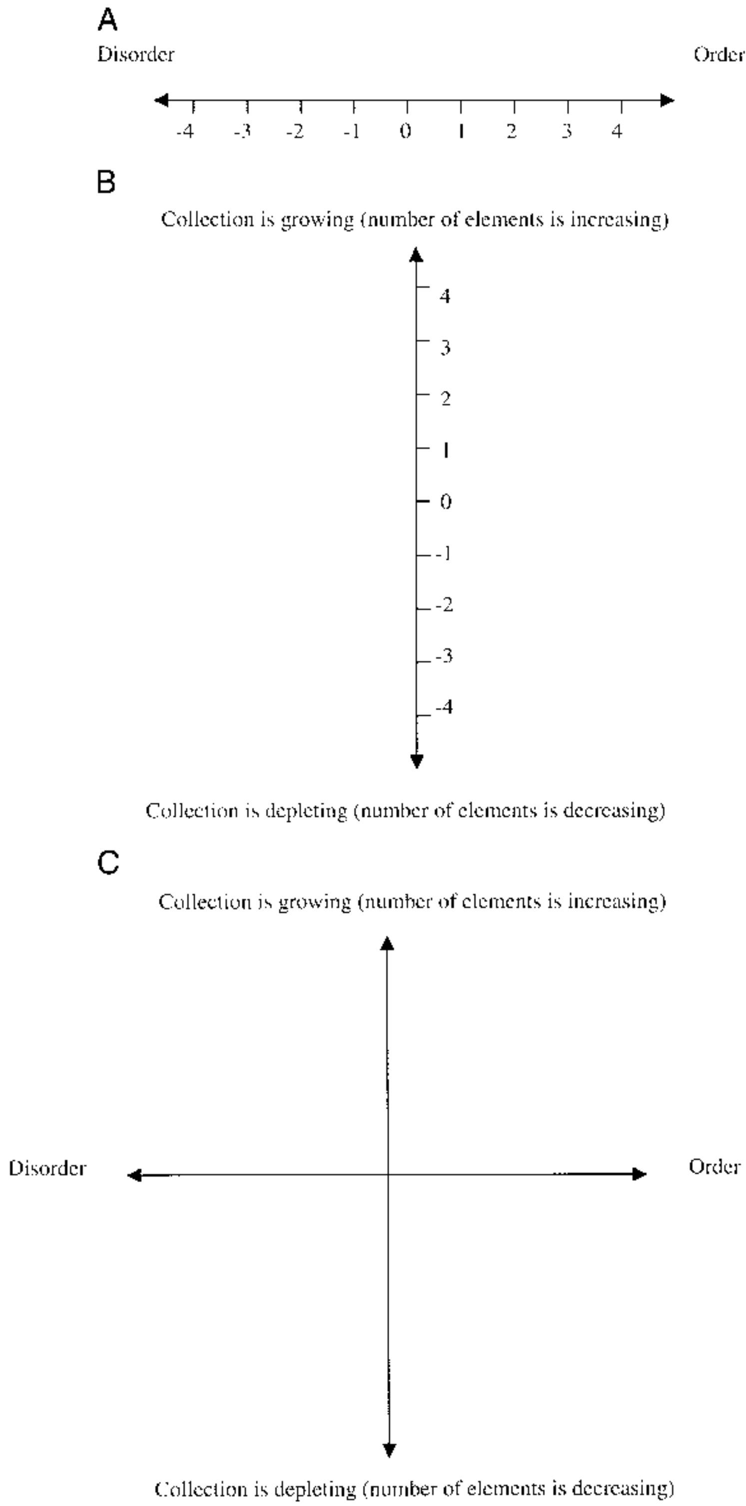

Figure 1. Graphic representation of the management of collections. A. Order (x-axis); B. Collection growth (y-axis); C. Collection Management.

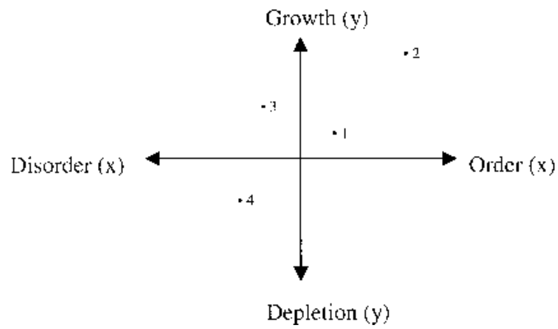

Figure 2. Graphical representation of collection situations. 1. p (1, 1), a stable and ordered collection; 2. p (4, 3), an ideal collection—growing but remaining in order; 3. p (−1, 2), a collection that is growing but falling into disorder; 4. p (−2, −2), a collection that is becoming disordered and decreasing in size.

axis, depicted as the y-axis (Fig. 1B). The collection may be growing (with the addition of new elements) or depleting (with the loss of elements due to custodial neglect, consumptive use, or deaccessioning).

Depletion of a collection is not always easy to detect, as it may occur simultaneously with collection growth, and thus may be masked by the growth. Significant collection depletion has occurred in many museums, particularly in the oldest institutions. Comparisons of museum catalogs from the 1600s and 1700s with specimens surviving in collections today indicate that a significant loss of specimens has occurred in these collections (Impey and MacGregor 1985, Murray 2000, Whitehead 1970, 1971). Most collection depletion is due to the limitations of preservation technology. Many of the standard techniques and chemicals used in collection preparation and care are actually detrimental to the useful life span of the collection elements (Hawks 1990, Williams 1999, Williams and Hawks 1987). This problem is often not recognized because collection deterioration is a much longer-term phenomenon than the working life of a curator. Most processes of collection deterioration are very slow (Rose and Hawks 1995, Waller 1995)—during a working life of 30 or 40 years, a curator may not notice the gradual deterioration of the individual elements of the collection. There is a lack of long-term studies of preservation and deterioration as well as a lack of accelerated aging studies of natural history collections (Duckworth et al. 1993, Hawks 1990, Williams 1999).

The mid-point for the y-axis is defined as the point of *stasis,* at which the collection is neither growing nor depleting (Fig. 1B).

The order axis (x-axis) and growth axis (y-axis) combined present a more complete representation of collection management (Fig. 1C). The location of an element (an object or a specimen) or a set (the collection) can be determined relative to these two axes. A point p (x, y) may represent a single element of the set (C) or the generalized location of the set (C) (Fig. 2). A better representation of the collection results when the set (C) is plotted as a cluster of points, each of which represents an individual element in the collection.

The third function of collection management is depicted on the z-axis, or the *conservation axis,* which describes the state of preservation of the collection elements (Fig. 3A). The mid-point on the z-axis is defined as the condition of a

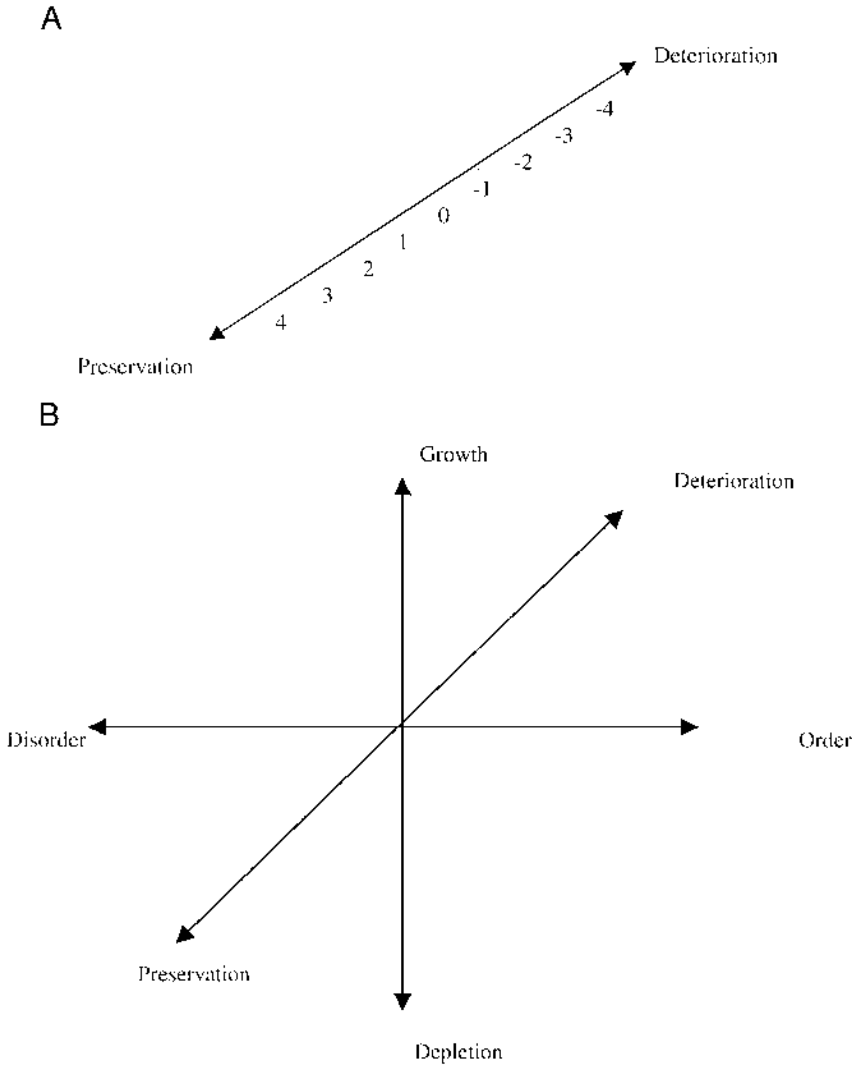

Figure 3. Graphic representation of collection management. A. The conservation axis (z-axis); B. The complete graphic of collection management.

specimen upon its receipt in the collection. Positive conservation reflects any stabilization or improvement in the conservation status of the element (such as rehousing in archival materials). Negative conservation is the result of deterioration of the element from its condition when received (such as a cellulose chain undergoing scission due to acid hydrolysis).

When these three axes are combined, they present a graphical representation of three considerations of collection management: (1) order, (2) growth, and (3) preservation (Fig. 3B). The three axes intersect at their points of stasis, or balance, such that the intersection of the axes is described as p (0, 0, 0). In actuality, the points representing the collection elements are seldom clustered at the intersection of the three axes. Collection elements are always distributed unevenly. When the

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collection is graphed as a set of points (each point corresponding to a collection element) forming a three-dimensional cluster in xyz-space, the shape and position of the cluster of elements making up the set (C) describes the collection as a whole.

The Measure of Order and Disorder: Entropy

William Thompson (Lord Kelvin) proposed the concept of entropy when he defined the second law of thermodynamics in 1853 (Kuntz 1968, Lightman 2000). The word *entropy* was introduced in 1865 by Rudolph Clausius (Lightman 2000). Entropy (S) is a measure of change (d), for example, the tendency of a closed system to move from a complex state to a more simple state. Entropy may be a reversible change (e) with an input of energy into a system from the outside (d_eS), as when the efforts of a collection care worker restores order to disordered collection elements; or an irreversible change (i) which occurs without an input of energy from the outside (d_iS), such as the deterioration of a fossil from pyrite disease. A reversible change in entropy is a *non-spontaneous change* (pushed by an outside force); irreversible entropy is a *spontaneous change* (Prigogine 1994). Systems of the reversible (d_eS) type can either increase or decrease in entropy (Lightman 2000), depending on the input of energy from outside the immediate entropy system. Left to itself, any spontaneous natural process proceeds in only one direction, driven by an increase in entropy, thus, a spontaneous change in nature, such as the deterioration of an organic compound, results in a change to a state of greater disorder (greater entropy).

In information theory, ''. . . order is described as the carrier of information because information is defined as the opposite of entropy, and entropy is a measure of disorder. To transmit information means to induce order'' (Arnheim 1971: 15). In considering collection management, we may derive a corollary from this concept—the facility with which information that can be obtained from a collection is inversely correlated to the degree of disorder (entropy) in the collection. Furthermore, we know that entropy is a function (f) of the number of different ways (m) in which an ordered state can be realized (Fast 1962). Thus, entropy may be quantified as $S = \mathrm{f(m)}$. There are many ways to order a collection, but not all of them are equally useful. The preferred method for ordering the collection is the way that produces the value for S closest to zero. This is the order that allows the elements to be retrieved from and returned to their cells with the lowest investment of resources. Minimizing or maximizing the complexity of order (such that $S < 0$ or $S > 0$) decreases the information that can be obtained from the set (the collection). Maintaining proper order (such that $S \approx 0$) increases the information obtainable from the set.

Entropy is also a probability statement about a system, because the entropy of a system increases as the number of possible states increases (Lightman 2000). In the case of collections, the number of possible states (m) may be equal to the number of cells in which the collection elements may be located, or the number of ways in which the specimens may be arranged within those cells. Entropy thus increases with collection size (the more cells there are in a collection, the more elements there are to be displaced from their cells, and the more possible incorrect arrangements of the elements in the cells), such that larger collections have more entropy than smaller collections. Probability theory predicts that the amount of resources (energy) necessary to reduce the rate of entropy increases geometrically as collection size increases arithmetically, an important consideration for the allocation of collection care resources.

A collection contains many elements. Each individual element may start to increase in entropy at random, and continue until it is eventually deaccessioned from the collection. As stated by Waller, ''the state of disorder in a collection is a summation of a bunch of little disorders in the collection'' (R. Waller, pers. comm. 1987). To evaluate the status of a collection, it is necessary to consider the degree of disorder of all of the elements of the set. This can be done by determining the placement of the individual elements of a collection in xyz-space. Evaluation of the location and shape of the cluster of collection elements allows predictive statements to be derived about the status and the future of the collection, serves as a guide in setting collection care goals, and helps determine the costs of collection management. For example, in an irreversible (d_iS) system (e.g., organic specimens), the inevitable increase in entropy means that the shape of the collection cluster will, over time, inexorably drift toward negative values on the z-axis. The goal of collection management is to slow this transition as much as possible, while preventing the collection cluster from entering the negative spaces of the x-axis and y-axis. In this model of collection management, the individual elements (1) will inevitably and irreversibly drift into the negative region of the z-axis; and (2) will be subject to drift into the negative regions of the x-axis and y-axis in a dynamic, but reversible fashion.

Much of the *cost of management* of a collection is the cost of reducing the rate of entropy in the collection. It is probable that ''zero'' entropy is a price that no collection can afford. The lowest possible entropy requires the highest costs to achieve. In fact, some amount of entropy indicates that the collection is thriving, or is being used. Considering these aspects, the question becomes this: what is an acceptable level of entropy in a collection? An acceptable level of entropy is when (1) there is order in the collection (which is to say, each element has its own cell); (2) growth does not exceed the ability to assign elements to cells; (3) the loss of elements is minimized; (4) each element can be found with a minimum of effort; (5) no single element is displaced from its cell for a prolonged period of time; and (6) element deterioration is slowed as much as possible. In a well-managed collection, the cluster of elements of the set in xyz-space rises and falls about the x-axis and y-axis, while remaining relatively stable about the z-axis. A certain level of order can be maintained in a system over the long term, yet some amount of entropy will always be present. The objective is to maintain a manageable level of entropy, indicating that the collection is used but that this use does not adversely affect the order of the elements, the preservation of the elements, or the growth of the collection. However, given an acceptable level of entropy in a collection, the cost of controlling entropy increases with the growth of the collection because $S = f(m)$.

Control of the Rate of Entropy

Some changes in entropy can be prevented (d_eS), others can only be slowed (d_iS). In either case, it is important to understand the forces of disorder and deterioration that affect collections. In preventive conservation theory, these have been grouped into categories as the *agents of deterioration*: direct physical forces, theft, vandalism and displacement, curatorial neglect, fire, water, pests, pollutants and contaminants, light and radiation, incorrect temperature, and incorrect relative humidity (Costain 1994, Michalski 1994a, Rose and Hawks 1995, Waller 1995).

Direct physical forces.—These are cumulative or catastrophic forces of irreversible entropy (d_iS). Waller (1995) delineated a series of states of these physical forces acting on collections, characterizing them as mild/gradual, severe or catastrophic. He characterized their occurrence as constant, sporadic, or rare.

Theft, vandalism, displacement, and curatorial neglect.—These are human activities that affect collections by disordering and damaging specimens. Because these forces are theoretically avoidable with proper allocation of resources, they are characterized as reversible (d_eS) entropy.

Fire.—Fire causes fundamental, irreversible (d_iS) chemical and physical changes in specimens or objects that are heated or burned. Fire has secondary effects in that collection elements that are not burned may still need to be cleaned because of their exposure to the fire, or they may have been damaged by the fire suppression system.

Water.—Exposure to water produces both reversible (d_eS) and irreversible (d_iS) dimensional changes and other damage in most natural history collection elements.

Pests.—With the use of integrated pest management, pests should be a controllable (d_eS) system. The damage caused by pests, however, is permanent (d_iS).

Pollutants and contaminants.—These are the results of changes in entropy in other systems that, in turn, affect the collections. These changes may be reversible (d_eS) (e.g., inert dust) or irreversible (d_iS) (e.g., sulfur dioxide, SO_2). Most contaminants produce permanent changes in collections.

Light and radiation.—All forms of damaging radiation are cumulative in specimens and therefore are irreversible (d_iS) factors. Most radiation damage is preventable (e.g., by blocking ultraviolet exposure).

Incorrect temperature.—Temperature may be incorrect if it is too high, if it is too low, and when it fluctuates excessively. Heat generally accelerates chemical processes (an increase in temperature means an increase in molecular movement); heat and cold both cause dimensional changes in the structure of specimens and objects, which result in stress damage. Incorrect temperatures are an expression of irreversible (d_iS) entropy.

Incorrect relative humidity.—Relative humidity is incorrect if it is too high, if it is too low, and when it fluctuates excessively. Incorrect relative humidity may be expressed as either irreversible (d_iS) or reversible (d_eS) entropy.

Entropy and Collection Storage

Collection elements react continuously with even very small changes in their environment. All collection elements (and the media used in documentation) are susceptible to deterioration over time; this deterioration will be accelerated if collection storage presents incorrect environmental conditions. Preventive conservation theory predicts that the best storage environment for collections and documentation is the most stable storage environment (within an appropriate range of temperature and relative humidity). Preventive conservation theory also predicts that it is most cost-effective to achieve a correct storage environment if the same type of materials are stored in the same storage area—for example, dry preparations in one storage environment, specimens in fluid in another. This is generally referred to as like-with-like storage.

Entropy and the Theory of Enclosures

It is easier to control collection storage conditions at the microenvironment level than the macroenvironment level (Weintraub and Wolf 1995), and microenvironments are easier to control using the principles of the theory of enclosures. The theory of enclosures was derived as a theoretical model by Michalski (1994b), based on leakage rates, and further developed by Rose and Hawks (1995) and Waller (1995). The basis of the theory is that the more enclosures that are provided around a collection element, the lower the rate of environmental (air) interchange, therefore the more stable the internal environmental conditions and the better protected the element is from the agents of deterioration. According to the theory of enclosures, each container that encloses an element (an element in a box, the box in a drawer, the drawer inside a cabinet, which is inside a room, inside a building) forms a protective barrier around the specimen. The better the integrity of each enclosure, the better the protection of the specimen from the agents of deterioration (including fluctuations in the storage environment). The theory predicts that enclosed storage furniture provides significantly more protection for collections than open storage furniture, thus in terms of collection care resource allocation, it is usually better to use an inadequate enclosure than no enclosure at all. For example, it is better to put curtains on shelving than to use open shelving. In general, some enclosure is almost always better than none. According to Michalski (1994b), leakage from an enclosure may be expressed as mass flow, volume flow, or exchange rate. Michalski concluded that ‘‘exchange rate best represents the notion of leakage as an inherent quality of an enclosure’’ (1994b:170). Leakage from enclosures is a measure of the change in entropy, and thus reflects the effectiveness of the storage system. An obvious corollary is that collection care resources should be directed towards improving enclosures beginning with those that enclose the most collection elements.

A small effort, such as the erection of a barrier to block an agent of deterioration, may significantly slow the rate of entropy because the progress of entropy is an energy function (R. Waller, pers. comm. 1987). The better the barrier, the more entropy can be slowed. In collection management, good collection handling procedures themselves can be good barriers. The establishment of a barrier requires an input of directed energy, but the amount of energy required may be very small compared to the resultant reduction in entropy. For example, the closure may be replaced on a leaking container of fluid preserved specimens, or the lighting on a taxidermy mount may be equipped with an ultraviolet filter. Undirected (random) energy will not result in the slowing of entropy, but rather in its increase. Thus, undirected or random energy inputs (such as elevated collection storage temperatures, or fire in the collection) should be avoided; but directed energy should be focused on establishing barriers to the increase of entropy in the collection.

Assigning Values to Measures of Entropy

When the individual elements of a collection are assigned coordinates in xyz-space, the resultant shape that is formed and its location describes the collection,

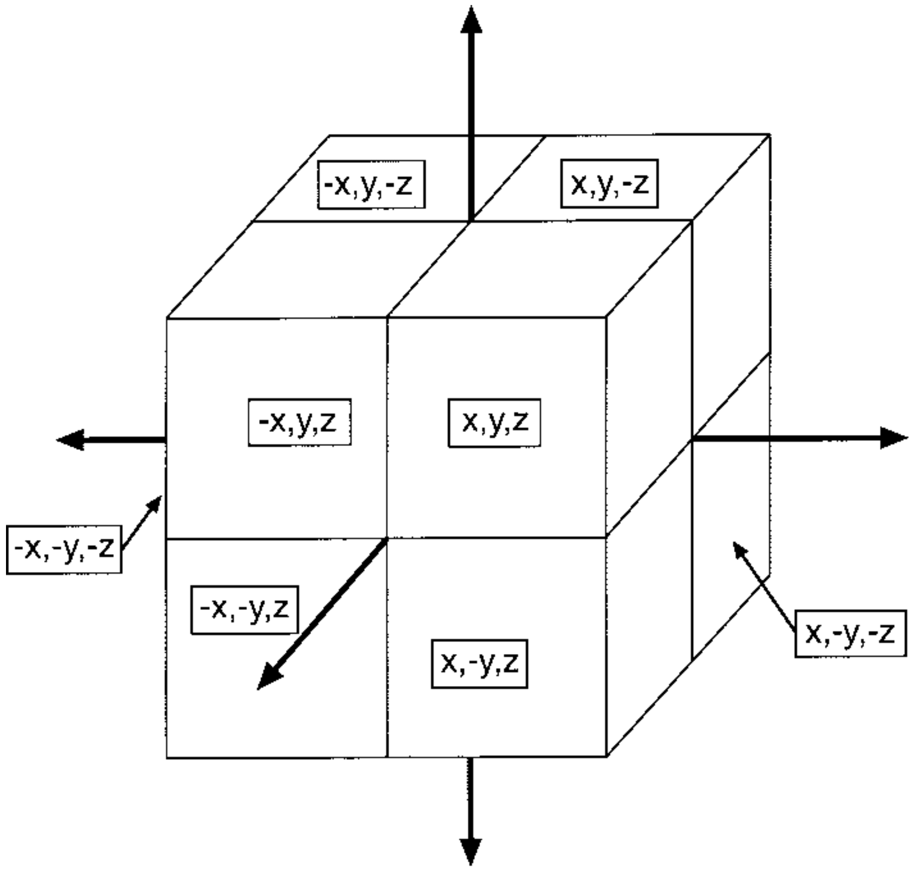

Figure 4. Octant characteristics of x,y,z-space: (octant) (x, y, z), (characteristics) order, growth, preservation; (x, −y, z), order, depletion, preservation; (x, −y, −z), order, depletion, deterioration; (x, y, −z), order, growth, deterioration; (−x, y, −z), disorder, growth, deterioration; (−x, y, z), disorder, growth, preservation; (−x, −y, z), disorder, depletion, preservation; (−x, −y, −z), disorder, depletion, deterioration.

enables predictions to be made concerning the future status of the collection, and provides a basis for decisions regarding the most effective allocation of collection care resources. Values on the three axes can be assigned to collection elements either on an individual basis, a relative basis, or a combination of the two. For example, values on the x-axis (order) could be either an actual count of the number of elements not in their cells, or a relative number expressing the degree of disorder in the collection relative to the degree of order. Values on the y-axis (growth) could be the actual count of elements lost and added to the collection, or a number expressing the ratio of elements lost to elements added. Values on the z-axis (conservation) could be the actual count of elements deteriorating or stabilized, or a number that reflects the relative deterioration or stabilization of elements of the collection. The position of the collection elements in xyz-space can be interpreted in conjunction with other collection assessment methods such as the Collection Health Index (McGinley 1993, Williams et al. 1996). In general terms, the characteristics of each octant of xyz-space are shown in Figure 4.

Conclusions

All natural history collections are managed—some well, some poorly, some by design, others by neglect. Collection management was once seen as a fairly simple concept—bring order to chaos, and then maintain the order. Because of this perception, who is in charge of the collections is frequently the result of historical accident rather than design (Simmons 1993). With the growth in size and complexity of natural history collections, and the tremendous increase in our knowledge of how to care for these collections, the current trend in natural history museums is to employ professional collection managers. In the past, the collections were under the direct care of researchers usually titled ''curator'' (Ford and Simmons 1997). However, scientists do not have the time or the specialized technical knowledge to care for collections. The body of knowledge necessary to care for a collection—preventive conservation, materials science, storage environment, integrated pest management, collection management policies—is outside of the training and knowledge base of traditional curators (Simmons 1993). It is not reasonable to expect researchers to manage and care for collections. If collections are to be preserved for future use, the care and management of the collections has to be carried out at a professional level by persons trained in the theory and techniques of collection management to maintain an equilibrium between current use and preservation for future use (Cato et al. 1996, Williams and Cato 1995). We must apply our knowledge of entropy, enclosure theory, and preventive conservation theory to direct the investment of resources to maximize the effectiveness of collection care.

Acknowledgments

We thank Camilo José Flórez for helping define the midpoint of the order axis; Philip S. Humphrey for first posing the philosophical question, ''how much entropy is acceptable in a collection''; Robert W. Waller for first explaining how entropy applies to collections; and Stephen L. Williams for numerous philosophical insights. Philip S. Humphrey, Sally Y. Shelton, and Robert W. Waller provided insightful criticisms of an earlier draft of this manuscript.

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Associate Editor: Ryntha Johnson