To James J. Gibson and Gunnar Johansson, two friends in science, whose exemplary work inspired the conference on which this book is based, and whose exemplary lives as scientists continue to inspire us all, we respectfully and affectionately dedicate this second volume in the series, Resources for Ecological Psychology.

PERSISTENCE AND CHANGE

Proceedings of the First International Conference On Event Perception

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10

The Physics of Controlled Collisions: A Reverie About Locomotion

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> *No fact of behavior, it seems to me, betrays the weakness of the old concept of visual stimuli so much as the achieving of contact without collision—for example, the fact that a bee can land on a flower without blundering into it. The reason can only be that centrifugal flow of the structure of the bee's optic array specifies locomotion and controls the flow of locomotor responses. (p. 14)*
>
> *But to understand, to be able to explain and predict, entails the knowing of laws. It is our own fault if we do not know the laws. (p. 15)*
>
> —J. J. Gibson (in Reed & Jones, 1982)

INTRODUCTION

Imagine the following scenario. It is late in the afternoon and since early morning you have been mulling over a long term concern of Gibson's (1950, 1960, 1961,

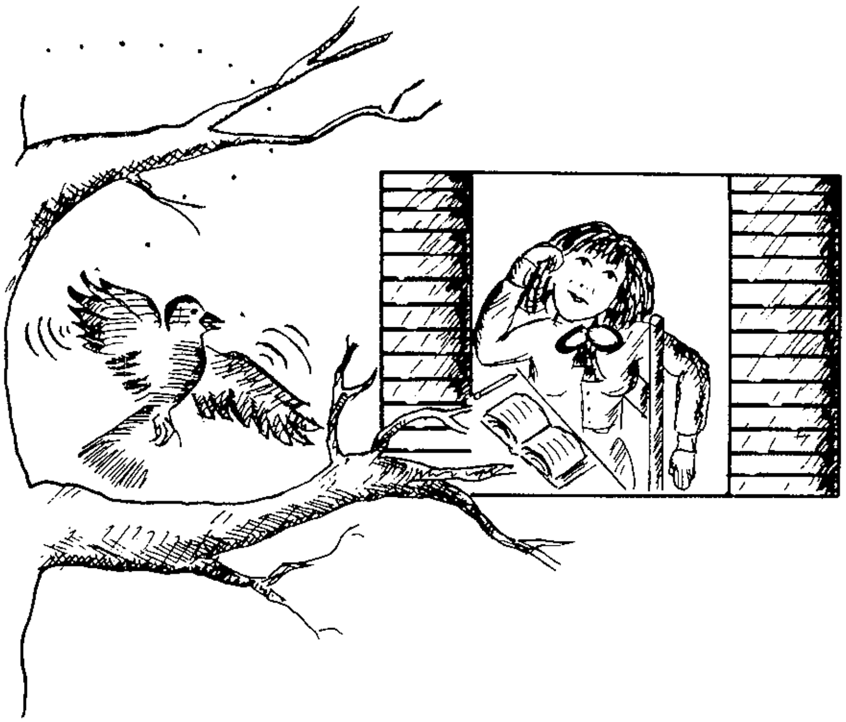

FIG. 10.1. Observing controlled collisions.

1966, 1979), namely, the optical structure ambient to an animal that is generated by the layout of surfaces and by the animal's movements (both the movements of its limbs relative to its body and the movements of its body, as a unit, relative to the surface layout). You are taken by the subtlety of Gibson's point that this optical structure resembles neither the surface layout nor the movements but it is specific to them because it is nomically (lawfully) dependent on them. And you are impressed by Gibson's insistence that these dependencies between properties of the animal-environment relation and properties of the ambient light are instances of laws, indigenous to the ecological scale (the scale of animals and their environments), that make possible the control of activity.

Your thoughts return repeatedly to locomotion, Gibson's favorite example, and to his characterization of locomotion as a matter of controlled encounters (Gibson, 1979) with the substantial surfaces that comprise the objects and places of the animal's niche. In the course of locomoting, an animal's surfaces may contact surfaces of the environment. These contacts are selective and they vary in intensity. There are hard contacts (as in predatory attacks), medium contacts (as in diving into water), soft contacts (as in alighting on a branch) and noncontacts (as in steering between trees). It seems to you that it might prove helpful to know what happens to bodies, in general, when they collide. And to this purpose, you direct your reading to the physics of collisions (summarized in the Appendix).

Your attention begins to wander. Looking out the window you see a bird in flight (Fig. 1). You admire its ability to adjust its flight to the surroundings. Your thoughts meander—"laws," "controlled collisions," "a physics of the ecological scale." You fall asleep and dream. . .

THE REVERIE

You are a physicist investigating a type of visible particle whose identity is unknown to you. Particles of this type range in mass from .001 kg to 10,000 kg. You watch the trajectory of a token particle through a nonuniform, three–dimensional surround as depicted in Fig. 10.2. In some regions of the surround, matter or energy is more concentrated than in other regions. The particle sometimes moves between the particularly dense regions and sometimes it contacts them. The particle's speed is not uniform. There are obvious decelerations and accelerations prior to contact, but these are not uniform either. Sometimes contact is preceded by a marked deceleration so that the contact is gentle—very little momentum is exchanged. Sometimes the deceleration prior to contact is hardly noticeable or there is an obvious acceleration so that the contact is violent or hard—a great deal of momentum is transferred to the contacted region. And sometimes the deceleration is in an intermediate range, such that the contact is neither gentle nor especially violent.

Not all the particularly dense regions of the surround are stationary. Some regions move just like the particle. Other regions move, but without the variations in accelerations that characterize the particle. Basically, the particle's trajectory with respect to the moving parts of the surround is not different from its trajectory with respect to the stationary parts: There is a steering among moving regions and contact—ranging from soft to hard—with moving regions.

Repeated observation of the particle's behavior with respect to the surround leads you to certain tentative conclusions as to its nature.

Conclusion 1. In tracking the particle's behavior, you monitor the mechanical quantity of momentum. The rate of change of momentum identifies a force or interaction between particle and surround. Usually momentum and its first derivative prove sufficient for the purpose of describing a given particle's trajectory. For the behavior of this particle, however, it seems that there is another mechanical quantity that is much more relevant: The second derivative of momentum or *the rate of change of force*. Characteristically, as the particle approaches a region of the surround, it exhibits a systematic sequence of acceler-

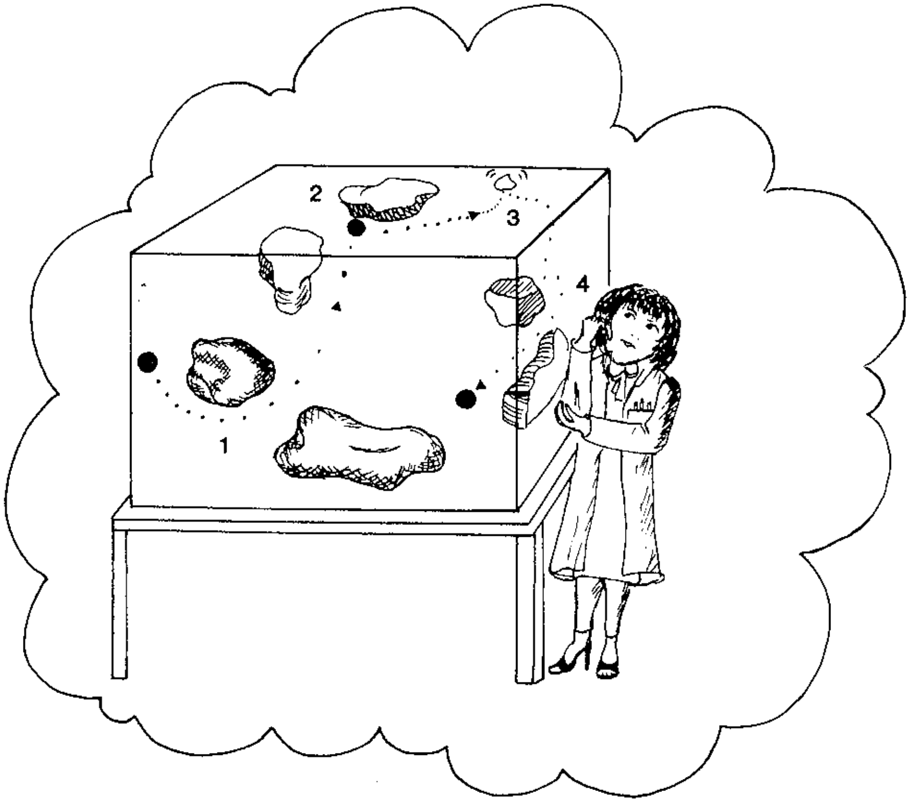

FIG. 10.2. As the particle moves through a nonuniform surround, it sometimes steers between dense regions (1 and 4) sometimes contacts them gently (2) or violently (3), and does not maintain a uniform speed.

ative changes. You wish to give this mechanical quantity a name. ''Jitter'' comes to mind but for obvious reasons you are attracted to ''control'' and you make note of the control quantity's relation to the more familiar mechanical quantities of momentum, impulse, and force (Table 1).

The *control* of a collision (read in the same sense that one would read ''the *momentum* of a collision'' or ''the *force* of a collision'') is, therefore, measurable. It would be given by the integration of C within the spatial and/or temporal limits of the collision, assuming that they can be reasonably approximated. Because of the fact that the mechanical quantity of control is a natural extension of the mechanical quantity of force, you are willing to speculate that there is a (scalar) quantity that relates to control in the manner that potential (a term referring to the concentration or distribution of a conserved quantity such as energy) related to force. Ordinary language usage suggests the term *coordination* for this quantity. The suggestion is fortunate: Both ''potential'' and ''coordination'' are configurational notions. You are tantalized by this idea that the conceptions of control and coordination may be interpreted as mechanical quantities that are as principled in their relation to one another as are force and potential.

TABLE 10.1

Quantity	*Symbol*	*Composition*	*Dimensions*
MOMENTUM	P	MV	MLT^{-1}
IMPULSE	I	ΔMV	MLT^{1}
FORCE	F	$\Delta MV/T$	MLT^{2}
CONTROL	C	$\Delta MV/T^2$	MLT^{-3}

[Where M = mass, V = velocity, T = time, Δ = change, L = length.]

Conclusion 2. It is evident that while proximity to things in the surround is a determinant of the forces forming the particle's trajectory, it is neither the sole determinant nor the most significant. Conventional particle trajectories are shaped by interactions with regions—usually other particles—which attract or repel a particle to varying degrees depending on the particle's distance from them. A force that is a function only of distance is termed ''conservative.'' The forces affecting the trajectory of your particle seem to depend on time (the time-to-contact) and, perhaps, velocity (the velocity prior to contact). They are *non*-conservative forces. You guess that these forces—which entail a dissipation rather than a conservation of energy—originate in the particle rather than in the surround. There is something special about this particle; it seems to have (on-board) a replenishable source of potential energy that it can deploy.

Conclusion 3. The number of soft, medium, and hard collisions; and non-collisions, exhibited by your particle during a period of observation is very large. Given so many interactions, you think it worthwhile to adopt a statistical mechanical orientation toward the particle's behavior. It seems particularly promising to inquire about the distribution function that characterizes the many interactions of the particle and surround. In the tradition of Boltzman, Maxwell, and Zipf you look to the distribution function as a way of appreciating the constraints—the quantities that must be conserved—on the interactions of particle-like entities. Relatedly, you see the usefulness of the distribution function for classifying particles. Types of interactions will be broadly distinguished by the quantities conserved over interactions; these differences in conservations will show up as differences in distribution functions given that a distribution function is *completely* determined by the operative conservations.

In the construction of a distribution function one asks, roughly, how many particles (in any arbitrarily chosen volume) will possess a particular value of a particular quantity. Boltzman and Maxwell focussed on gases and the property of velocity. Over the very many interactions of n particles of a gas, the conservations of total mass (nmv^0), momentum (nmv^1) and vis viva (nmv^2, or twice the kinetic energy) determine that the particles will tend to move at one particular speed, more or less. Collectively, the conservations select ("prefer") a distance between collisions (mean free path) and a time between collisions (mean relaxation time). The mean and variance (the "more or less") of the velocity reflect the concentration of the conserved quantities. The mean and the variance of the velocity prove to be characteristics of a gas, and both are affected by its temperature.

Thinking about your particle in comparison to a gas particle you are of the opinion that the contrast between the two is most sharply drawn with respect to momentum change in relation to velocity. Impulses of gas particles are of maximum frequency when the velocity of the particles is zero, that is, at the moment of impact. At any other moment impulse is nonexistent. Statistically, your particle could be assigned a mean free path and a mean relaxation time but, importantly, across the full range of velocities that it exhibits, impulses can be observed. Unlike the gas particles, there is no velocity at which the frequency of impulses is concentrated.

You imagine a distribution function defined over three coordinates: number of particles, velocity, and number of impulses. For a typical gas and for particles of the type you are studying the distribution functions differ significantly. The peaking of impulse frequency at zero velocity that reflects the conservations governing the gas will not be found in the distribution function of your particle type. What does the absence of a peak (the fact that impulse is uniformly distributed over velocity) mean? The distribution function for your type of particle must be the way it is because of the conservations that are operative. This is true by definition. However, the conservations governing your particle's behavior cannot be the typical velocity-linked conservations of mass, momentum and energy. *The conservations governing your particle's behavior are velocity indifferent.*

Conclusion 4. Although you are unable for the present to say much about the selectivity of the trajectory—the fact that some regions function as attractors and some as repellers—it is clear to you that the particle's trajectory *minimizes the mometum transferred to the particle from the surround.* What sort of principle is the particle subject to that demands no momentum bumps? If the particle's interior was complex and if its persistence depended on maintaining that interior, then keeping the level of momentum absorption below some critical value would clearly be important—large transfers of momentum could fracture the particle (see Appendix). At the level of the particle this principle reads: *move so as to conserve a smooth unitary process* ("smooth" meaning no sudden energy or momentum bumps—excessive energy or momentum exchanges—and "unitary" meaning that the characteristic form and function of the particle is preserved). As a physicist, however, you might be uncomfortable with a conservation that is (1) defined at the level of the individual particle; and (2) not identified with a quantity. The traditional conservations of mass, energy and momentum are in reference to measurable physical quantities exhibited by the particle. Further, the invariant nature of these quantities is not defined at the level of the individual particle but minimally at the level of a pair of interacting particles. For example, with regard to momentum conservation, the momentum of each of two individual particles may change with a collision but the summed momentum of the two particles after collision equals the summed momentum of the two particles before collision.

Your discomfort with the notion of a conservation of a smooth, unitary process might be alleviated (but not eliminated) by the observation that some of the so-called quantum numbers conserved in the collisions of subatomic particles denote a qualitative property—the class of the particle—that is invariant at the level of the individual particle. You note how well leptons (approximately eight particles that do not take part in "strong" interactions) conserve their class membership; accelerating a lepton such as the positron to the point where its mass is equal to that of a proton (a member of the baryon class of particles that *do* take part in "strong" interactions) does not result in a metamorphosis. Nevertheless, you would be happier with a more traditional orientation to conservation, given the size of the particle you are studying. You suppose that your particle might be a member of a class. Is there a conserved quantity defined at the level of the class? For example, over the many trajectories of the many members of this class, perhaps the number of members is conserved.[1] If a quantity such as the latter had to remain constant then the minimization of momentum transfer from surround to particle (and hence the conservation of a smooth, unitary process) would be rationalized.

Conclusion 5. You recognize that a circumstance, such as the one you are studying, in which forces are shaped to achieve one trajectory and to prevent others, usually defines a machine. Somehow a machine conception must be brought to bear on your understanding of the particle. Because a machine is a way of harnessing mechanical forces to do work in determinate directions, a machine can be properly termed a constraint—a restriction on the laws of motion. Very often a machine is constructed with hard, resistant pieces linked by hard, resistant chains. Is your particle a hard-molded machine like this? What

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[1] Iberall (1977) has suggested that the number of members of a biological species is approximately conserved and a physics that accommodates biology will require the addition of this conservation to the list of conventional conservations.

makes you dubious is that a hard-molded machine is not very flexible and the particle's trajectory indicates that the shaping of force to achieve gentle, medium and violent collisions, or to avoid collisions, *is* flexible. The rate of change in the rate of change of the particle's momentum (i.e., the control) varies from region to region of the surround. The unavoidable conclusion is that the forces are harnessed by a constraint that cannot be hard-molded. To draw the comparison, you might say that the constraint on the nonconservative forces centered in the particle is "soft" rather than "hard" and that the appropriate machine conception is soft-molded rather than hard-molded.

Conclusion 6. Because you must avoid postulating action at a distance, you make the assumption that *the soft constraint on the particle-based forces is a field.* This field is ambient to the particle. Is it a field associated with a force, a quantum field? Of the four fundamental forces only the gravitational and electromagnetic forces apply, given the magnitude of the particle. The electromagnetic field would seem to be a better bet than the gravitational, but neither is particularly appealing because you are convinced that *if the soft constraint is a field, it cannot be a field associated with a force.* It may well be caused by electromagnetic phenomena but it is qualitatively different from them.[2] Your conclusion follows in part from certain distinctions drawn by Pattee (1972, 1977). Forces and constraints are not things of the same type, even though constraints—like all other aspects of nature—are built from the four fundamental forces. To begin with, the forces are not embodied in anything particular and they apply to everything within the range to which they apply (gravity, for instance, applies everywhere). A constraint, however, has a particular embodiment and applies to a particular thing. Further, whereas the important feature of a force, its magnitude, is dependent on rate (the derivative of a variable or variables with respect to time) the important feature of a constraint, its selectivity (resulting in one directed motion rather than others), is not dependent on rate.

Conclusion 7. It is a small step from the preceding conclusion to the conclusion that if the field in question is *not* a force field then the fundamental dimensions from which its relevant variables are constructed cannot include mass (M). That is, the field must be kinematic—of fundamental dimensions length (L) and time (T)—or geometric—of fundamental dimension L, but it cannot be kinetic[3]—of fundamental dimensions, M, L, and T. As you have already noted this field must constrain the dissipative forces focused in the particle so as to keep to a minimum the momentum transferred to the particle from the surround. You puzzle over this requirement. Doesn't it mean that the field in question must be structured by the kinetics of the surround and the kinetics of the particle? If the field did not faithfully reflect these two kinetic domains then there would be no lawful basis for relating forces originating in the surround to forces originating in the particle and the exchange of momentum could not then be regulated. You suppose, therefore, that the field in question has this capability and inquire what this tells you about the general properties of the field.

To bring things into focus, you assume (1) the particle to be in motion at a constant velocity in one direction; and (2) an absence of motion in the surround. Normally you would represent this by a velocity vector originating in the particle and pointing in the direction of travel. However you find it convenient to think of the field hydrodynamically—as a fluid flowing relative to the particle. So instead of assigning a velocity vector to the particle (because you regard it as the origin) you assign a velocity vector (the negative of the particle's velocity) to each point in the field, where each field point can be anchored to a surround point.

This vector flow field viewed strictly as a kinematic field is always at equilibrium; there is no tendency *on the part of the field* to restore its structure following a disturbance. Further, from the perspective of the flow field, a disturbance is reversible in that any disturbance and its reverse are energetically equal. This reversible, equilibrium character of the flow field is because the flow field is not paying the energy cost, so to speak, of its changes. That bill is being paid by the *kinetic* field—the particle—to which the flow field is coupled: Only changes in energy flux can give rise to changes in flow, and the changes in energy flux in this case are bound to the particle's on-board energy reservoirs or potentials.

The reversibility of the flow field appears to be of paramount importance. If the flow field were not reversible, if it carried potentials that "wound up" the trajectories, then the flow field would itself determine some of the properties it exhibits. A reversible field on the other hand, meets the criteria of linearity—superposition and proportionality—and can, therefore, faithfully map the kinetics that give rise to it. You feel that there may well be a very general principle here: *The availability of a reversible field is a prerequisite for the kind of controlled collisions that your particle exhibits with respect to its surround.*

What properties arise in the flow field caused by the particle's motion relative to the surround? A coarse analysis reveals the following: kinematic properties, consisting of (1) *transformations defined over the entire flow field*—such as outflow from a point and inflow to a point; and (2) the *inverse of the rate of dilation* of a topologically closed region of the field; and (3) geometric properties viz., *singularities,* such as foci of outflow and inflow.[4] Global transformations (1) are specific to the displacement of the particle as a unit relative to the surroundings (moving forward or backward); the inverse of the rate of dilation

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[2] Gibson's optic array (1961, 1966, 1979) seems to be a field of this type.

[3] Gibson repeatedly pointed out that optical motion is altogether different from material motion—that optical motion has no inertia (for example, Gibson, 1979).

[4] Properties of this kind were identified by Gibson (1966, 1979) for the optical flow field resulting from the locomotion of an animal in a cluttered environment.

(2)—a property you recall reading about in the astronomer Hoyle's science-fiction novel *The Black Cloud* (1957)—is specific to the time at which the particle will contact a region on its path while the first derivative of this property, which is seen to be a dimensionless quantity, is specific to the deceleration of the particle with respect to the approach region.[5] The foci of flow (3) will be specific to the regions, or to the gaps between them, toward which the particle is moving; that is, the foci are specific to the direction of the particle's trajectory.

It is obvious to you that under normal circumstances, the style and/or rate of transformation will not be uniform throughout the entire kinematic field; rather, there will be discontinuities caused by region boundaries that will identify more precisely the relationship between the moving particle and a particular layout of dense regions (depots of mass). For example, within the global outflow "local" properties will be revealed, such as: (1) a gain of structure inside a closed contour in the field specifies an opening in a dense region through which the particle could travel; (2) a loss of structure outside a closed contour in the field specifies an obstacle to the particle's current trajectory.[6]

Clearly, motion of the particle gives rise to properties that do *not* exist when the particle is immobile. The properties identified above, both kinematic *and* geometric, are annihilated when the temporal dimension goes to zero and the ambient kinematic field is reduced to an ambient geometric field. For example, "streaming" engendered by the particle's motion condenses out geometric, rate-independent points, the singularities, that are not identified by a geometric field analysis. A geometric field analysis at any instant of time would not contain the singularities.

Conclusion 8. You are drawn to the fact that your cursory examination of the properties of the kinematic field (caused by the displacement of the particle relative to the surround) revealed a dimensionless number: The first derivative of a kinematic field property specifying time-to-contact. What intrigues you is the possibility of an analogy between the dimensionless quantities of the kinematic field (assuming that there are more to be discovered) and the dimensionless quantities that order a kinetic field, such as a hydrodynamic field.

The transition from one state to a qualitatively distinct state of a physical system usually indexes a critical change in the relation between two competing processes. Your favorite example is the transition from laminar flow to turbulence which occurs when the processes (viscous, dissipative, irreversible) that resist fluid motion cannot, in their current organization, balance the processes (inertial, conservative, reversible) that sustain fluid motion. The dimensionless Reynolds number gives an index of the competition between inertial (etc.) and viscous (etc.) processes. High inertial forces favor turbulence, with the pronounced internal shearing that that implies. High viscous forces prohibit sustained turbulence by damping motions that lead to discontinuity (e.g., eddies) and thus ensure laminar flow. The inertial processes are governed by Newton's law of inertia and the viscous processes are governed by the law for shear stress of a Newtonian fluid. The Reynolds number, therefore, might be described as indexing the relation between the two laws. On either side of the critical value of the Reynolds number the two laws are mutually cooperative whereas at a critical value one of the two laws dominates the other (that is, a competition occurs).

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[5] Lee (1976, 1980) identified this property for the condition in which a point of observation approaches, or is approached by, a substantial environmental surface.

[6] See Gibson's (1979) discussion of the optical support for the control of locomotion.

You are aware that, as a general rule, any major dimensionless number used in physics can be derived directly from the laws known to apply to the phenomenon to which the number refers (Schuring, 1980). A dimensionless number is often referred to as a Pi number (Buckingham, 1914), and when it is derivable from one or more laws it is termed a *principal* Pi number (Schuring, 1980). The important thing you note here is the linkage between physical states of affairs that principal Pi numbers index and the facts of critical values and behavioral modes (or natural categories). As you see it, the shift in balance between two (or more) laws governing a phenomenon from situations in which they cooperate to situations in which one law alone is responsible can produce categorically distinct states. The transition from cooperation to competition between governing laws is tantamount to a natural boundary making device: Behavioral modes are created, critical values of one or more variables are defined.

In sum, the critical values of dimensionless quantities in the kinetic cases mark off distinct physical states. It does not seem likely to you that dimensionless quantities will play this role in the kinematic field of constraint because of the absence of forces—by definition—in the kinematic field. But you cannot be too sure, one way or the other. For the present, however, it seems prudent to emphasize the specificational rather than the physical nature of the kinematic field. This emphasis raises the question: Do dimensionless quantities in the kinematic field mark off—at critical values—distinct *specificational* states?

A soft collision with no momentum exchange between the particle of interest and a nonmoving, dense region on its path requires that the particle decelerate. A deceleration is adequate if and only if the distance it will take the particle to stop with that deceleration is less than or equal to the particle's current distance from the region of upcoming contact. Your calculations show that for any particle of the type you are studying a deceleration is adequate if and only if:

$$P_i(\text{contact}) = \frac{d\tau(t)}{dt} \geq -0.5$$

where $\tau\ (t)$ is the time-to-contact variable of the kinematic field.[7] You state this

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[7] Lee (1976, 1980) performed these calculations and highlighted the significance of the first derivative of the time-to-contact variable. Other optically defined dimensionless quantities that order (at critical values) specificational states have been suggested and experimentally examined by Warren (1982).

result as follows: When less than −0.5, the dimensionless quantity, Pi (contact), specifies that the particle will experience a momentum bump if present conditions persist; when equal to or greater than −0.5, Pi (contact) specifies that the particle's contact with the upcoming region will involve no momentum exchange if present conditions persist.

You are encouraged by the results of your analysis. It does seem that *critical values of dimensionless quantities in the kinematic field distinguish between qualitatively distinct specificational states.* And it seems to you that the analogy should be pursued further. For example, you might ask: What kinds of laws go into the construction of pi numbers applicable to the kinematic field?

Conclusion 9. Because the kinematic field ambient to the particle constrains its trajectory, you infer that the field and the particle must be coupled. This coupling is obviously "soft" rather than "hard." The question to which you now turn is: What must be required of the particle and of this soft coupling if the particle is to be constrainable in a way that makes its collisions controllable? What must be true of the particle so that it can be reliably constrained by the kinematic field?

It appears to you that there are two important and very general conditions on the coupling. One condition is that the coupling be linear. What would have to be true of the particle's interior in order to guarantee a linear coupling? The interior of the particle could be in either a reversible or irreversible steady state. If it were reversible the distribution of conserved quantities would be (nearly) uniform and the interior would be (approximately) at equilibrium. This means that there would be no problem of "connectivity": A disturbance felt by any region of the interior could be transported to any other region of the interior, however remote. On the other hand, if the interior's steady state were irreversible then there would be marked and persistent source-sink gradients. As a consequence, a disturbance felt in one part of the interior may not be transported to other parts. Conservations are not carried up gradients and, conventionally, it is through the transport of conserved quantities that one part of a physical system "informs" another part about what it is doing. A loss of connectivity among the regions that accompanies irreversible steady states means that the overall effects of the kinematic field on the particle's interior—however those effects are realized—could be discontinuous and equivocal. In short, it seems to you that if the steady state of the interior were irreversible and far from equilibrium then there would not be a constant scale for laws relating properties of the kinematic field to force trajectories of the particle. You are led to assume, therefore, that a linear coupling, which would be both flexible and precise, requires a reversible, close-to-equilibrium steady state. This is tantamount to assuming that the state space of the particle's force trajectories are quasiergodic (that is, no strong preferences or dislikes): The particle should not be biased in a way that undercuts the specifying capability of the kinematic field.

The other condition on the coupling is that the criterial "smooth and unitary process" be upheld. This condition would be met only if the coupling involves very little energy (relative to the energy stored and dissipated by the particle). A coupling achieved at high energy expense might take too long (there would be steep external gradients) or it might involve a large momentum exchange and irreversible processes (marked by stress and shock waves). You conclude that there must be an energetically cheap translational gate effecting the coupling of the particle to the kinematic field.[8] Or, said differently, you conclude that the kinematic field is the spatio–temporal structure of a *low*-energy field. Your best hunch is that this low-energy field is the electromagnetic field modulated by the absorption/emission properties of the surround.

Conclusion 10. Some of your observations of the particle's trajectories are especially puzzling. Two of them are depicted in Fig. 10.3 and 10.4. In one observation (Fig. 10.3), you noted that your particle mimicked the trajectory of another particle of like kind. The two trajectories were, for a time, coupled. This coupling of trajectories did not depend on the distance between the particles. Sometimes you witnessed the coupling when the particles were very close (Fig. 10.3a). At other times you saw the coupling when the particles were separated by a substantial distance (Fig. 10.3b).

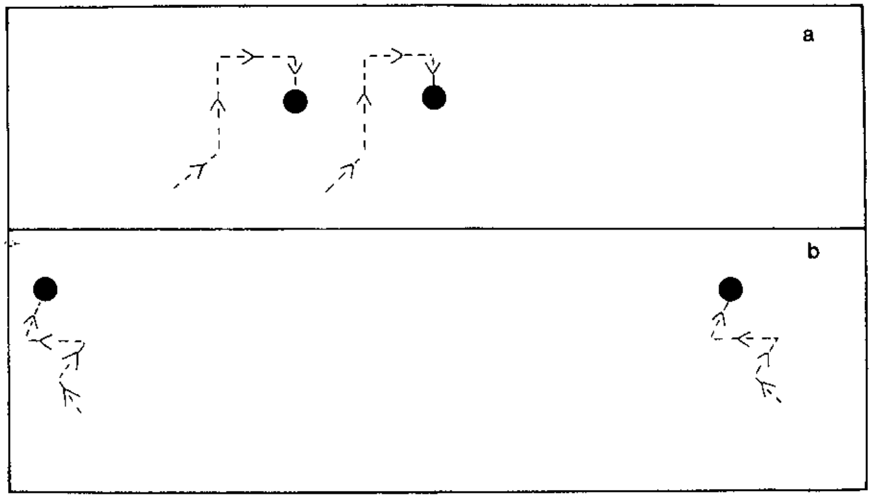

FIG. 10.3. The particle mimicks the trajectory of another at near (a) and far (b) distances.

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[8] For animals, the photoreceptor processes perform the role of a translational gate that involves very little energy relative to the animal's daily energy expenditure.

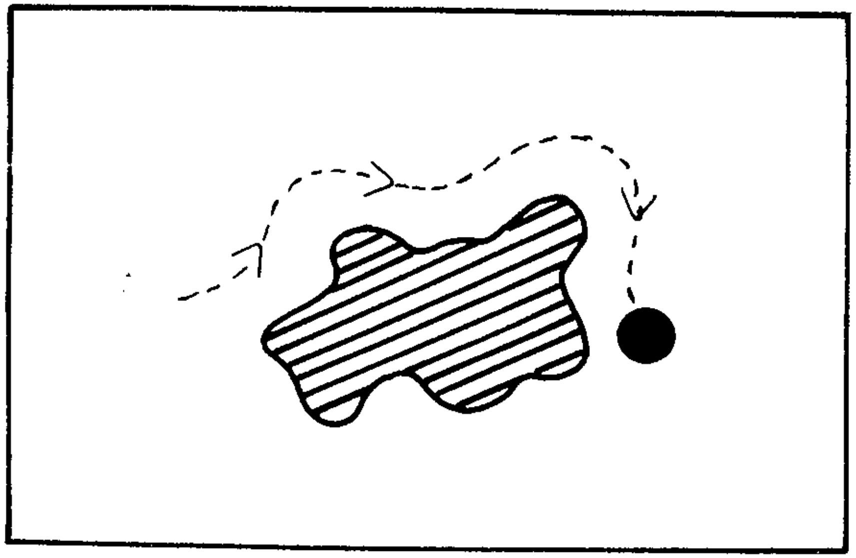

FIG. 10.4. The particle's trajectory follows the border of a dense region of the surround without contacting it.

In the other observation (Fig. 10.4) you noted that your particle's trajectory would follow, without contact, the border of a dense region in the surround. Here it seemed that there was another temporary coupling—between the form of the particle's trajectory and the form of a region.

Why do you find these observations especially puzzling? It is because, as a physicist, you are committed to explaining any coupling (coordination or cooperativity) of one thing with another through conservation principles, and it is not immediately obvious to you what the principles are that apply to the two couplings depicted in Fig. 10.3 and 10.4. If you had observed two, more conventional particles coupled in interaction, then you would have said that (1) some quantity was exchanged between the particles—at the very least momentum and energy; and (2) the coupling was an instance of coordination or cooperativity *because the exchange of quantities between the particles is constrained by the requirement that these quantities be conserved over the pair of particles.* You would explain the loss of degrees of freedom that marks an interaction between particles by an appeal to conservational invariants.

You feel, therefore, that you have no option but to identify the conservations that account for the coupling phenomena depicted in Fig. 10.3 and 10.4. Because the "mimicking" phenomenon is indifferent to particle separation, you believe that the conservations in question are unlikely to be energy or momentum related. Conventionally, couplings based on energy exchange depend on the distance between the particles (i.e., the inverse square law).

After a good deal of deliberation and hesitation you suggest the following: One of the conservations accounting for phenomena of the type depicted in Fig. 10.3 and 10.4 must be *conservation of topological form.* (You believe that this conservation is integral to these instances of cooperativity but recognize that this conservation alone cannot account for the loss of degrees of freedom). Your use of topological form is intuitive rather than technical. You mean, most generally, adjacencies and successitivies—that is, neighborhoods in space and time. And you mean, more particularly, properties of the kind captured in contrasts such as inner/outer, sooner/later, lower/higher, closer/further, slower/faster, larger/smaller, and so on. Further, your use of conservation is intended to mean that from one "slice" of the kinematic field that couples the particle to the surround to another, the topological form is constant. This conservation of adjacencies and successivities from a location proximate to the source to a location distal to the source is made possible by the reversible, equilibrium, low-energy nature of the kinematic field. Identifying the two particles in Fig. 10.3 as kinetic fields, it is clear that the adjacencies and successivities arising from one kinetic field are perfectly conserved over the distance that separates the two kinetic fields. The proof is in the adjacencies and successivities arising from the second kinetic field (your particle)—they duplicate those arising from the first.

Conclusion 11. A better stab can now be made at the machine conception befitting the constraining of the forces that determine the particle's trajectory. You have come to the understanding that whatever the machine conception, it cannot apply just to the particle; rather, it must apply minimally to both the particle and to the kinematic field that is lawfully generated by the surround and the particle's displacement relative to it. It is very obviously true that the particle and the kinematic field are distinguishable. They clearly are different materially and, further, the particle, as a source of forces, is a kinetic field. Given that they are so different, you are puzzled by the principle that relates them as a single machine.

Now you are set to thinking: What, after all, is a machine? Turning to examples of hard-molded machines you are struck by the fact that they are always closed kinematic chains, where a chain consists of kinematic pairs of elements, for example, shaft and bearing, bolt and nut, etc. Each element in a pair, because of its resistant material qualities and its form, envelops and constrains the other so that all motions except those desired in the mechanism are prevented. There is kinematic closure. You can appreciate why a thoughtful student[9] of hard-molded machines might say that *a machine consists solely of elements which correspond, pair wise, reciprocally.* Kinematic closure is the central principle governing the construction of hard-molded machines.

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[9] Such as Reuleaux (1963).

Two other features of hard-molded machines capture your attention. First, in a closed pair of elements the roles of "fixed" and "moveable" can be exchanged (for example, the nut can rotate and translate relative to the fixed bolt or the bolt can rotate and translate relative to the fixed nut). This inversion of roles causes no change in the motion belonging to the pair as you show in a sketch (Fig. 10.5). In both of the situations shown in your sketch the separation between the nut and the head of the bolt is decreasing. Second, although it is common for a pair of elements to be completely closed in terms of bodily envelopment, it is not necessary. The closure that prevents certain motions from occurring can be achieved without material structures; you note, for example, how vertical downward closing forces keep the wheels of a train in contact with the rails.

It occurs to you that this invariant characteristic of hard-molded machines—reciprocally constraining, kinematic pairs—may well be an invariant characteristic of all machines, including the soft-molded machine you are trying to understand. Are the paired elements of this machine, the particle and the field ambient to the particle, kinematically closed? If there is a generalizable principle of kinematic closure, as you suppose, then the particle and the ambient field should pass the inversion test: For example, fixing the entire surround and moving the particle in one direction should have the same consequence as fixing the particle and moving the entire surround in the opposite direction. In the diagram (Fig. 10.6) situation A should be indistinguishable from situation B.

Your empirical validation proceeds as follows: You note a location where the particle frequently comes to rest. (It is natural to assume that this location is a singularity—a stable location of minimal potential energy—in the particle–surround system.) You then arrange matters so that on the next occasion that the particle is immobile at that location the entire surround moves relative to the particle. You observe that the particle displaces in the same direction as the surround.[10] You conclude that the vector flow field lawfully generated by the displacement of the surround in direction +X specifies a displacement of the particle from the singularity in direction −X. Hence, the particle displaces in direction +X toward the singularity.

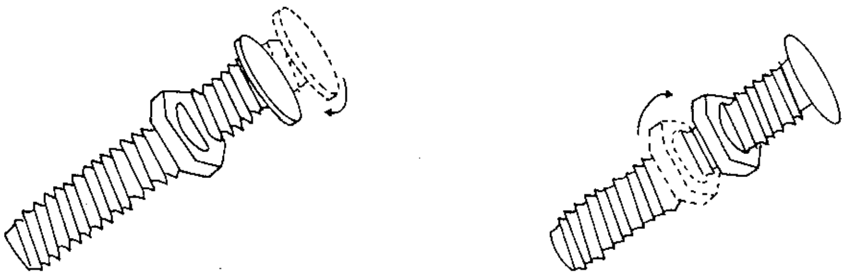

FIG. 10.5. An example of a hard-molded machine. The distance between the nut and the head of the bolt can be decreased either by turning the bolt relative to the fixed nut as in (a) or turning the nut relative to the fixed bolt as in (b).

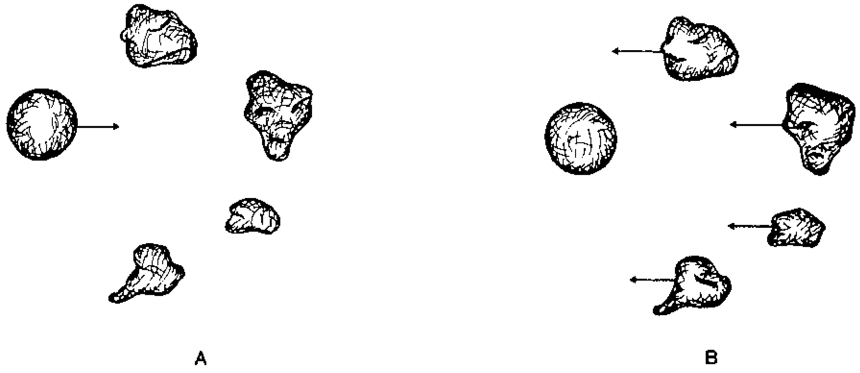

FIG. 10.6. An example of a kinematically closed soft-molded machine. The distance between the particle and the surround can be decreased either by moving the particle relative to the fixed surround as in A or moving the surround relative to the fixed particle as in B.

This kind of kinematic closure differs from the most familiar types. The two familiar type you have already remarked upon might be labeled (1) kinematic closure through resistant bodies; and (2) kinematic closure through forces. The kinematic closure you are now promoting is (3) kinematic closure through specification. The three types are alike in that the realization of any particular motion requires that a special relation hold between the paired elements. You are convinced that if you were observing your particle on a rectilinear trajectory toward a given region of the surround and you intruded on the flow field by some means so as to introduce a prolonged rotational component into the flow field, then the rectilinear trajectory would not be maintained. To realize any given trajectory of the particle, a symmetry must exist between that trajectory and the flow field: For the particle to move clockwise there must be a counterclockwise flow; for the particle to move toward p there must be a flow centered at p, and so on. Although it is very clear to you that for your particle and its ambient field this symmetry always holds, the point that you wish to underline is that *in the absence of this symmetry an "intended" trajectory cannot be satisfied.*

You are absorbed by what the foregoing reasoning implies, namely, that there might well be a similitude for all machines, hard-molded and soft-molded. The invariant feature of machines seems to be kinematic closure achieved by reciprocal contexts of constraint; kinematic closure seems to be founded on a

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[10] Lishman and Lee (1973) have shown that in a room where the walls and ceiling can move as a unit, displacement of the room causes a person standing in the room to topple in the direction of the room's movement.

symmetry between the paired elements. To your journeyman understanding, this symmetry reads: There is a transformation T such that if A and B are the paired elements, then $T(A) \rightarrow B$ and $T(B) \rightarrow A$. You recognize that this transformation T is the mathematical notion of a *duality operation* and that the elements A and B are mathematical *duals.* You pose the question: What is the significance of the duality nature of machines? Tentatively you answer that if the prerequisite for constraining forces to produce selective, determinate motions is a duality structure then *duality must be a symmetry property of the most basic kind.*[11]

Conclusion 12. In controlled collisions the particle must produce changes in force that are commensurate with changes in the kinematic field. Two examples come to mind: (1) to effect a soft collision any fluctuations in P_i (contact) that carry this quantity below its critical value must be countered by fluctuations in the control quantity, C, that are of commensurate amplitude; (2) if the surround is caused to fluctuate, so as to produce oscillatory global outflow and inflow of the kinematic field, the particle's position will similarly fluctuate, 180° out of phase.[12] The particle's commensurate fluctuations are the result of force changes in proportion to flow changes.

Your earlier conclusions about the conditions of the coupling of particle and field are incomplete. They do not identify *a principled physical basis for force differences that are proportional to flow differences.* When considering hydrodynamic flow you normally visualize a process in which an inhomogeneity in potential gives rise to a force that drives a flow. More generally, differences in potential (ΔP) gives rise to difference in force (ΔF) that, in turn, give rise to differences in flow (ΔV): $\Delta P \rightarrow \Delta F \rightarrow \Delta V$. Flows are proportional to forces, and where the Onsager condition holds, sensible deductions can be made in many instances from the macroscopic hyrodynamic flow to the irreversible thermodynamics that is its basis. The problem your particle poses is different from this conventional problem. It reverses the causal path and asks how flows can give rise to proportionate forces. Here, the causal vocabulary looks strained. But you are aware that you have felt this strain throughout your analysis. Thus you have spoken of the kinetic fields (particle and surround) as *causing* the kinematic field and the kinematic field as *specifying* and, cognately, *constraining* the kinetic field.

You remind yourself of some basics: Changes in motion or flow per se cannot cause changes of force; there can be no forces where there are no potential differences; the trajectory of force depends on the form of the potential. You surmise that *if a flow is to affect a force it must do so by modifying the potential from which the force is derived.* Modulating a potential would not necessarily cause a change of force; generally, other conditions must be satisfied. This reservation is consonant with your observation of the influence of the flow field on the particle: only *global* changes in flow lead invariably to changes in force. So, a change in force may or may not occur given a change in flow but what you are after is a lawful basis for these changes whenever they do occur.

The problem has been refocused: *How could a flow affect a potential?* Formally a force F is defined as the negative of the potential inhomogeneity or, more presently, gradient, viz. $F = -\nabla P$, where the gradient symbolized by ∇ is a spatial gradient. If P is identified as the particle's on-board potential which is taken to be nearly homogeneous (given the arguments you made about the reversible, close to equilibrium steady state of the particle—Conclusion 9) then you must look to the kinematic field as the source of the inhomogeneity, that is, as specifying a *spatial operator,* ∇. Now, by taking the first derivative of both sides of the above expression for F you get:

$$dF/dt = -d(\nabla P)/dt;$$

that is, control (see Conclusion 1) is given by the rate of change of the product of the spatial operator and the potential. In the foregoing context the first derivative of $-\nabla P$ defines a temporal gradient. As with the spatial gradient, you take the temporal gradient to be an operator specified by the kinematic field. Assuming commutativity the preceding expression for the control quantity can be written:

$$dF/dt = -\nabla dP/dt = -\partial^2 P/\ X_i dt,$$

where ∂X_i is the spatial operator and dt is the temporal operator. In sum, the answer to the question of "how could a flow affect a potential?" seems to require the recognition and understanding of space and time operators on potentials. Given that the units of space and time must be in the scale of the particle—expressed in terms of the mean free path δ and the mean relaxation time τ of the particle's interior—the control quantity ought to be reducible to an expression in P, δ changes and τ changes.

As a further point, the ordering of potential, force and flow that you are suggesting here is different from that which follows from considerations of hydrodynamic flow, namely: $\Delta V \rightarrow \Delta P \rightarrow \Delta F$. It would be prudent, however, to relate the two orderings. You go for the most obvious relation:

$$\begin{tikzcd}
\Delta E \arrow[rr] & & \Delta V \arrow[dl] \\
& \Delta P \arrow[ul] &
\end{tikzcd}$$

The flow field (ΔV) and energy flux ($\Delta P \rightarrow \Delta F$) are linked in "circular causality." You underscore that these two "paths" of influence are not the same. First, the flux-to-flow path is a change in layout (e.g., a flow is produced when the particle as a unit displaces relative to the layout of the surrounding regions) whereas the flow-to-flux path is through the translational gate you

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[11] This point has been argued by Shaw and Turvey (1981).

[12] See Lee (1978).

identified in Conclusion 9. Second, comparatively speaking, the flux-to-flow path is energetically expensive whereas the flow to flux path is energetically cheap (see Conclusion 9). (You resist identifying these paths with the cybernetic notions of "forward-fed" causality and "backward-fed" causality. You feel that such a move is regressive given that the notions of feedforward and feedback imply a referent signal, a comparator and, more generally, a separate controller. The origin and functioning of each of these would have to be rationalized by physical principles. [As a physicist you wish to explain the phenomenon of controlled collisions without the introduction of controllers sui generis.] Moreover, you feel that the different labeling of the pathways, as forward and backward, although well motivated in artifactual situations, is arbitrary in natural situations.)

Conclusion 13. A controlled collision is a physical event in space–time. It is, however, by the conventional theory of physical events, a very odd kind of event. You struggle to formulate its heterodox quality: *A controlled collision is a space–time event in which the final conditions of a particle's motions determine the values that the initial conditions must assume.* (You had observed repeatedly, for example, that when the particle softly collided and when it violently collided with a region of the surround its accelerative change prior to collision was initiated at two different marginal values of the time-to-contact property.) This heterodox quality suggests to you a structure of space–time peculiar to controlled collisions, one that is explicitly shaped by *both* initial and final conditions. As a physicist you are well aware of the need to be clear on the space–time structure of events. Without a prescription for putting space–time boundaries on an event the determination of its causal basis remains very much a guessing game. Within what limits should you try to close the bookkeeping on the relevant summational invariants—the conservations? You turn your attention to conventional physical event theory to see how well it fares in this regard and to see what modifications will be required.

In the conventional theory, "observer" refers to the measurement of the location of an event in space–time. As a local reference system or inertial frame, the observer must be perspective free. Measurements must be made simultaneously and distributively throughout a given region of space–time. The "observer," therefore, must be capable of existing everywhere in a specified region of space–time. Your particle "observes" and "measures" (its surroundings and its relation to them). However, given that it is of finite size (rather than being infinitely small) and can exist in only one place at any one time it cannot be identified with the observer in orthodox physical event theory: *Your particle must have a perspective.* You suspect that this fact will be of importance in the eventual formulation of the laws of controlled collisions.[13]

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[13] For Gibson (1966, 1979) the structure of an optical flow field is always exterospecific *and* propriospecific—it is always specific to the layout and to the observer.

Corollary to the absence of a real or natural perspective in physical event theory is the absence of an historical perspective. While the present is causally constrained by the immediate past, it is not (to borrow a term from Bertrand Russell) *mnemically* conditioned by the distant past. You sketch for yourself the Minkowskii diagram (Fig. 10.7) that illustrates the causal light cone which is the traditional domain of physical event theory. (Fig. 10.7b is a simplified version of Fig. 10.7a with x, y, z reduced to a single spatial (s) axis.) With the speed of light as the limiting boundary, only those events within the same forward light cone can be causally connected to the present event at the origin, $t = 0$ (because there are no known superluminal signals, events outside the light cone cannot be connected with those inside). The events leading up to the present are nowhere represented. The premise of the orthodox theory is that the past is instantiated in the present and that, together with the laws of motion, is sufficient to predict or explain event outcomes. The particle you have been studying makes you skeptical of this premise. Somehow the final conditions must be brought in—explicitly—to accommodate controlled collisions.

You try to close in on what this would require by producing a series of modifications of the Minkowskii diagram. First, you include a past light cone which converges at $t = 0$—the event from which the forward or future light cone diverges. In your modified sketch (Fig. 10.8) you have rotated the axes so that time flows from left to right. Next, you depict four events in your sketch (Fig. 10.9). The events E_1, E_2, and E_3 are on the same world line where E_3 is causally constrained by E_2 and E_2 is causally constrained by E_1. You take pains to note that the causal constraints are not necessarily transitive for these interactional sequences (that is, E_3 is not necessarily causally constrained by E_1). This is because E'_2, which is on a world line with E_3, might cancel (or otherwise alter) the effects of E_1. While E_1 transacts with E_3 in the context of E_3's historical

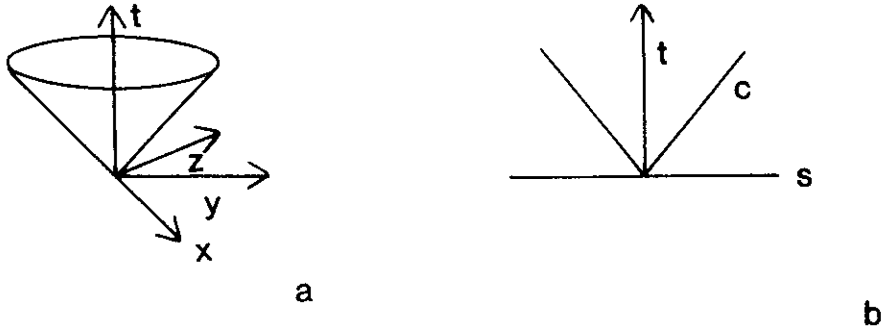

FIG. 10.7. (a) The causal light cone determined by time (t) and three spatial dimensions, x, y, and z. (b) The causal light cone where x, y, and z have been reduced to a single spatial axis (s), showing the speed of light, c, as the limiting boundary.

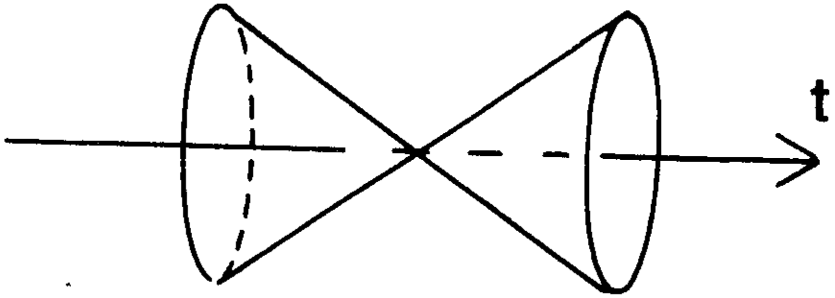

FIG. 10.8. A modified Minkowskii diagram rotated so that time flows from left to right. It includes a mnemic (past) light cone as well as the standard causal (future) light cone.

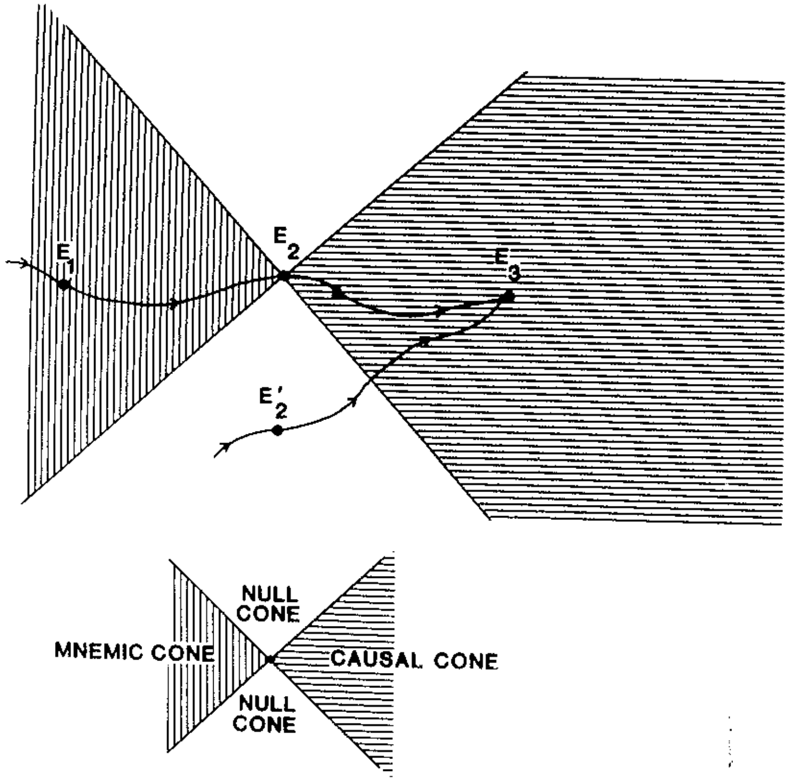

FIG. 10.9. The causal relationships among four events. Although E_3 is in the causal cone of E_2, it cannot be explained on this basis alone—E_2 exerts an influence on E_3, yet is in the null cone of (and, therefore, unknown at) E_2.

relation to E_2, it does not do so in terms of the historical context of E'_2. The rub, as you see it, is that because E'_2 is outside the forward light cone of E_2 (it is effectively simultaneous with E_2), its effects cannot be known at E_2 and, therefore, E_3 cannot be explained on the basis of E_2's causal cone alone.

Because unobservable events may exert an influence on future events, necessary paths of influence cannot be discovered by working forward from initial conditions to final conditions. You recognize, however, that determinant histories may be discovered by working back from the final conditions to the initial conditions. *All* of the influences on E_3 are in its past or mnemic cone. In sum, the causal future of E_2 is only partially accounted for by its forward cone but all of the determiners of E_3 are in its mnemic cone. There is an asymmetry between the information derived from history and the information applicable to the future.

You are inclined to believe that the only appropriate framework for controlled collisions must be composed of the causal and mnemic perspectives together. But is this framework to be one in which these perspectives remain asymmetric? Or, more accurately, is there a different level of analysis that may reveal the symmetry of the event space for controlled collisions? You pose this question because of a major lesson learned from orthodox physical event theory: Putting symmetry at the forefront reveals the structure of space–time and fetters the application of law. Knowing the symmetry that defines a space–time event means that if one element of an event is known, the nature of its symmetric counterpart is also known.

You modify your sketch of the Minkowskii diagram once again, this time creating a bounded region between the causal and mnemic cones of two succeeding events (Fig. 10.10). You are now ready to propose a *symmetry postulate for controlled collisions:* If (1) E_1 (approach to a region) and E_2 (contact) are on the same world line (where E_2 is in the causal cone of E_1 and E_1 is in the mnemic cone of E_2); and (2) there are no events outside the causal cone of E_1 that influence E_2; then E_1 and E_2 together define a new event—call it E_D—for which they are dual perspectives. The past and future cones have been merged into a higher-order event space. Events outside the bounded region have no existence for the particle; they are in neither its history nor its future. Events inside the bounded region have relative existence. The new event E_D is a controlled collision and it will be guaranteed whenever the symmetry conditions (1 and 2) hold.

In a further sketch (Fig. 10.11) you contrast dual events with nondual events. The events E_0 and E_1 are duals, the events E_2 and E_3 are duals, but E_1 and E_2 are not duals because condition (2) is violated (E_2 is influenced by E'_1 which is in the null cone of E_1). What you wish to show in this last sketch is that the specification of E_2 will be indeterminate when based on the causal cone perspective of E_1. Moreover, the selection of marginal values at E_1 to determine an outcome at E_2 is not guaranteed to be successful since the basis for controlling the outcome at E_2 is not completely available at E_1. A controlled collision cannot be defined over E_1 and E_2 because they are not duals.

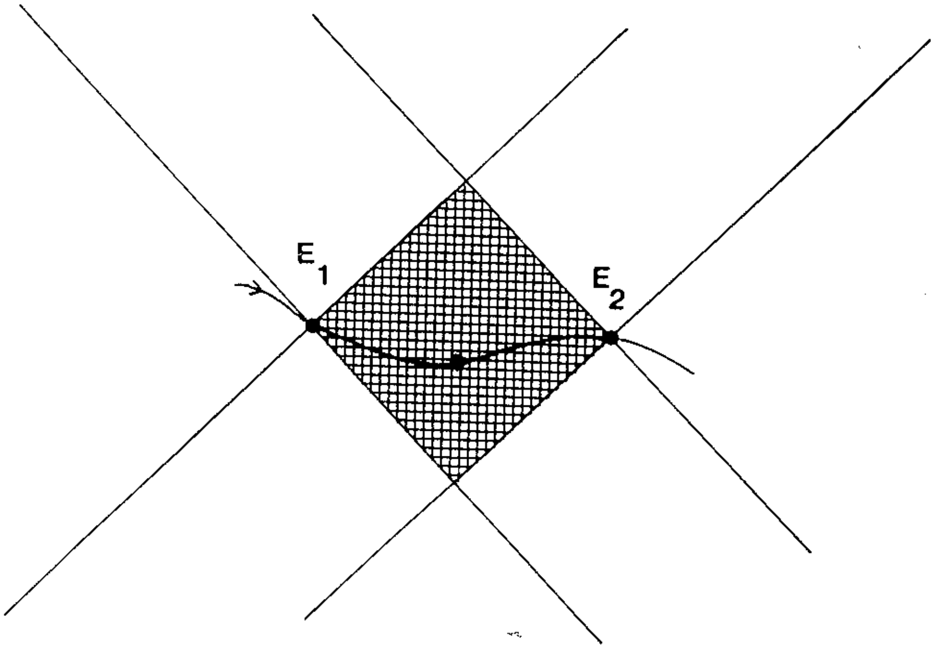

FIG. 10.10. The bounded region between the causal cone of E_1 and the mnemic cone of E_2 defines a new event, E_D, for which E_1 and E_2 are dual perspectives.

To restore or, more accurately, to reveal a duality you suggest a change in scale (Fig. 10.12). At the grain of a finer space–time mesh there necessarily exists some event E_2, causally proximal and dual to E_1, for which a controlled collision can be minimally defined. This change in scale merely assumes that the particle has limited sensitivity or acuity to distant events on its world line. (In fact, your observations of many particles of varying sizes reveal that there is a strong relationship between acuity and size. The spatial range is a constant proportionality of the vertical magnitude of the particle.[14] Simply put, large particles act with respect to things at a greater absolute distance than do small particles.)

Your point is that, for controlled collisions, any events antecedent to some future event toward which the particle's current behavior is directed (1) must lie within the particle's current causal perspective if they have significant effects on the particle's immediate future; or (2) must be trivial in their effect if they lie undetected in the particle's null cone. Because significant events cannot lie outside the bounded region of a controlled collision, *an appropriate scale of*

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[14] Kirschfield (1976) reports that for animals there is a simple first-order relation between visual resolution (R) and body-height (H), $R = k/H$, where k is a constant of proportionality.

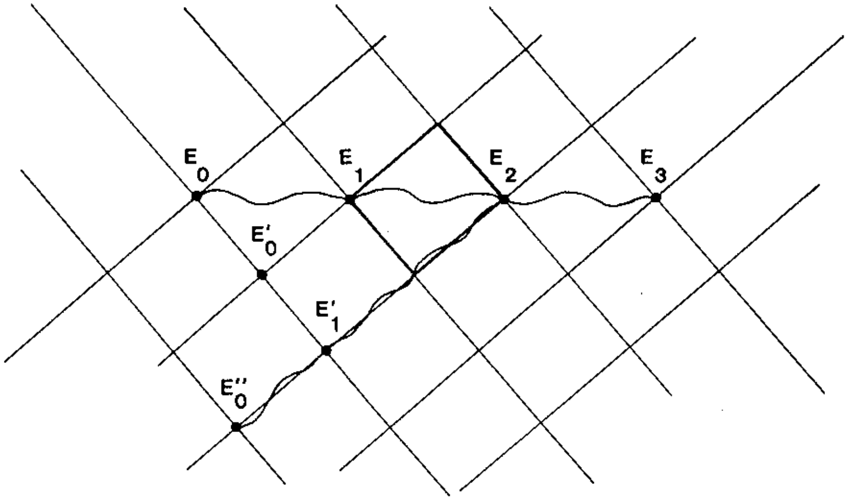

FIG. 10.11. E_0 and E_1 are duals (note that E''_0, though in the null cone of E_0, is *not* on a world line with E_1), as are E_2 and E_3 (note that E''_0 is at the limiting boundary of (and, therefore, is included in) the mnemic tone of E_2). E_1 and E_2 are not duals because E_1 influences E_2 but is in the null cone of E_1.

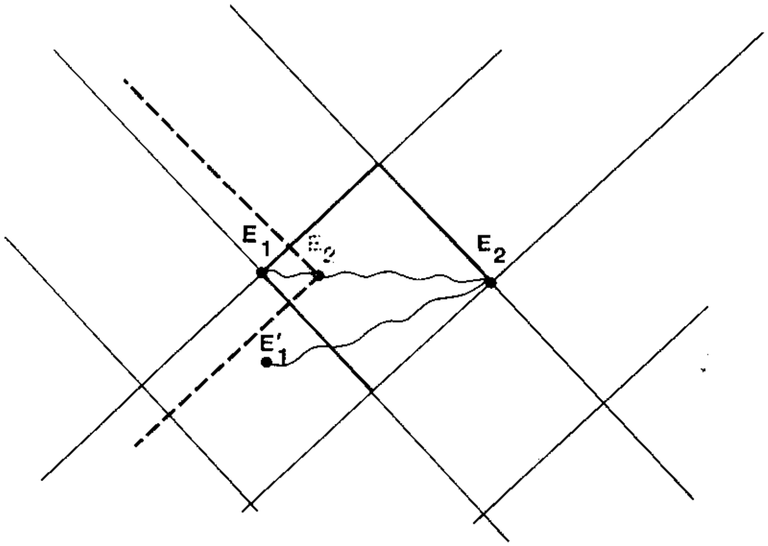

FIG. 10.12. Some E_2 must exist that is causally proximal to E_1. A change in scale reveals the duality over which a controlled collision can be defined.

analysis that satisfies this condition must exist. You insist that symmetry is the guide to finding this scale: Given either the perspective from the initial conditions or the final conditions, the other perspective is specified.

A SUMMARY AND AN AWAKENING

You have discovered quite a lot about your particle but its identity still eludes you. You convince yourself that you have all the information you need to identify this type of particle and it is only some firmly entrenched bias that prevents you from seeing it. You think that you may have given a physical description to the behavior of an entity that is usually considered to be outside the domain of physics. Several of its properties are like those of more standard particles but you have noticed they often include less standard twists. You review the properties you have discovered in the hope that highlighting the "twists" might fuel an insight. (At the very least, it will provide a convenient way to summarize these REM episodes.)

1. The behavior of your particle can be described with a measurable quantity ut this quantity is control ($\Delta MV/T^2$) rather than the more standard momentum MV).
2. Forces determine the trajectory of your particle but they are dissipative ather than conservative forces and they originate not in the surround but in the article. Moreover, the particle can replenish its energy supply.
3. The distribution function that you constructed as a means of classifying our particle reveals it to be in a class whose behavior is not governed by velocity ependent conservations.
4. Your particle exhibits conservation but it seems to be conservation of opulation number, rather than the more standard energy or momentum or mass. o accomplish this conservation, it appears to minimize momentum transfers hat might fracture the particle.
5. Because your particle harnesses forces to achieve selective trajectories, ou consider it to be in the class of machines. But its constraints are soft molded, llowing flexibility in the strength of collisions, rather than hard molded.
6. The soft constraint on the particle-based forces is a field, but it cannot be ssociated with a force.
7. Because the constraining field is not a force field, it cannot include dimension M and, therefore, is not kinetic; because certain properties that are necessary the control of collisions are annihilated when t goes to 0, the field must include imension T and, therefore, is not geometric. The soft constraint must be a inematic field.

8. Critical values of dimensionless quantities in the kinematic field distinguish between qualitatively distinct states, but these are specificational states rather than physical states as would be the case in a kinetic field.
9. Because the kinematic field constrains the particle's trajectory, it must be coupled somehow to the particle, but the coupling must be linear (so that equivocalities are not introduced) and low energy (so that it does not involve large momentum exchanges and irreversible processes).
10. You explain the coupling through a conservation but it is of topological form (adjacencies and successivities) rather than of energy or momentum.
11. The machine conception (identified in Conclusion 4) must apply minimally to the particle *and* the field as duals, not just the particle. The symmetry is necessary in order to realize and maintain trajectories.
12. The flow field produces proportionate forces in the particle, presumably by modulating a layout of potentials. Whereas the fact that forces produce flows proportionate to the forces is understood, the fact that flows produce forces proportionate to the flows is not.
13. Controlled collisions, which are characteristic of your particle, are physical events but the structure of space–time is shaped by final conditions as well as initial conditions. Where the particle is going colors how it gets there.

What is this soft-coupled duality of particle and surround, wherein collisions are guided by distinct specificational states that bring final conditions to bear on initial conditions, and are controlled by the dissipation of the particle's replenishable energy reserves in such a way as to minimize momentum transfers

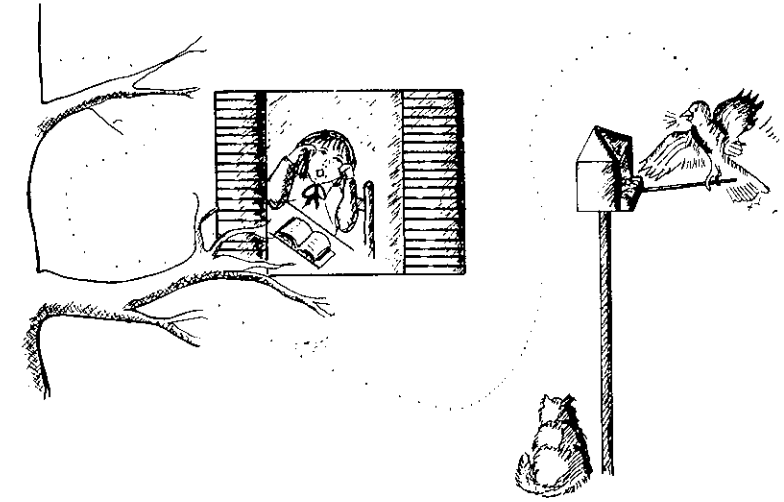

FIG. 10.13. The dreamer awakes.

that could fracture it? You seem to have described a physics of controlled collisions, but for what . . . or whom. . . ?

You are startled awake by the agitated chirping outside your window. The bird is hovering about a feeder in an effort to replenish its fuel supply but a cat has appeared on the scene waiting to replenish itself by effecting a violent, predatory collision on your friend. Fortunately for the bird, you muse theoretically, the imminence of contact with the cat is specified in the optical flow field that links properties of the animal to properties of the environment. You marvel, once again, as it guides its flight to avoid the cat and locate the food, cutting its speed just in time to alight gently on the feeder. Now those are the kinds of controlled encounters that Gibson wanted to understand and that you've been trying to understand. You are suddenly overcome with a sense of déja vu, with a feeling that, at some level, you have understood.

APPENDIX

A. The Theory of Collisions

The concept of collision refers to forces applied to and removed from an object in a very short period of time. The classical theory of collision, based primarily on the impulse-momentum law for rigid bodies, regards the colliding objects as single mass points. All elements of each object are assumed to be rigidly connected and to be subjected instantaneously to one and the same change of motion as the result of the collision. In reality, the forces initiate stress waves which travel at finite velocity away from the region of contact and through the object. These waves reflect from boundaries of the object and interact with stress waves still being generated at the region of contact to create a complex pattern of stresses and strains in the interior. In short, all regions of an object subjected to a collision are *not* exposed simultaneously to the same force conditions (Goldsmith, 1960).

The classical theory is most suited to ideal atomisms whose degrees of freedom are exhausted by the three axes of translation. Atomism is a term suggested by Iberall (1977) for an entity of any magnitude that is atom-like at the scale of the ensemble to which it belongs. It is conventional to say that ideal atomisms have no internal degrees of freedom, where "internal" has the uncommon meaning of "extratranslational." Atomisms of gases such as helium are closest to this ideal. They are single atoms each free to move on the three spatial dimensions. For all intents and purposes, the total energy imparted by collision to a helium atomism may be regarded as going into the translation of the atomism. In terms of the equipartition theorem, the energy received is divided evenly and completely among the atomism's degrees of freedom, which are all translational.

The atomisms of another gas, oxygen, introduce a measure of internal complexity. These atomisms (molecules) consist of two linked atoms. To define the position of each of the atoms of oxygen requires three degrees of freedom for a total of six. However, the linkage between the atoms eliminates a coordinate choice, thereby reducing the degrees of freedom of the oxygen atomism to five. Because translation of the oxygen atomism's center of mass consumes only three of the five degrees of freedom, the two degrees of freedom that remain are "internal." The equipartition theorem would assign three fifths of the energy of collision to the translation of the atomism and two fifths of the energy to the internal bond. Clearly, conservation of energy does not hold if only the energy carried by the translation degrees of freedom is taken into account. It is for this reason that collisions of atomisms with internal degrees of freedom are said to be inelastic and that the conservation of momentum (rather than of energy) is the dominant constraint on their equations of collision.

Consideration of the collisions of diatomic atomisms is a small step toward the collisions of *systems*. In a statistical mechanical sense a system is an ensemble of interacting atomisms with a boundary that prohibits the ensemble from dissolving into the surround. The atomisms of a system may be internally barren (like the helium atomism) or internally complex (of a kind hinted at by the oxygen atomism). As noted, internal complexity is associated with ways of absorbing the energy applied to a unitary thing other than through the translation of its center of mass.

B. The Theory of Fracture

The first major advance beyond the classical theory of collisions (viz., the one-dimensional vibrational treatment of colliding objects) recognized the significant proportion of energy converted into oscillations when the system's natural frequency is long compared to the duration of contact. Subsequent analyses of the multidimensional aspect of wave propagation consequent to collision, and of the stress distribution at the region of contact, were made possible by developments in the theory of elasticity (Timoshenko & Goodier, 1951). It suffices to say, for present purposes, that elasticity refers to the fact that the internally generated forces of restoration are comparable to the externally applied forces of deformation so that there is a return to the status quo ante on removal of the external forces.

In many collisions, however, the conditions of impact are such that the entire cross-section of one or both of the colliding objects will exhibit a final permanent strain of significant magnitude, or one or both of the objects may fracture. Such nonreversible phenomena result from the conversion of kinetic energy into permanent distortion or fracturing of the structure of the object and the eventual dissipation of this energy in the form of heat. The analysis of the irreversible deformations wrought by the propagation of stresses that exceed the elastic limit (so called plastic flows or plastic waves) is a more recent and less developed aspect of collision theory (Goldsmith, 1960).

Evidently, the responses of an internally complex system to collision will be difficult to follow. It is possible, nevertheless, to obtain some useful insights into the collision process by considering (1) the behavior of a system under statically imposed forces; and (2) the relation between impact parameters and system failure, ignoring the internal responses.

The deformation resulting from loading a system statically can be treated as a series of equilibrium states requiring no consideration of acceleration effects or wave propagations. Of major interest is the response to static loading of systems that exhibit a degree of rigidity, that is, systems which preserve their form in the face of perturbations. The requirement, of course, is that the system be elastic through some range of perturbation. Solids have an elastic domain as do multiphase systems that are solid or gel in part, such as living things that are dominated by elastic-plastic-fluid (liquid and gel) processes (Yates, 1982).

The interior of a solid system can respond in one of three ways to an applied force: (1) the linked atomism can be forced further apart or closer together than the equilibrium (minimal potential) distance; (2) atomisms can hop into adjacent vacant lattice sites; and (3) the bonds between the atomisms can be broken (Freudenthal, 1950; Nadai, 1950; Walton, 1976). If response 1 is sufficient to absorb the energy of loading the solid is operating strictly within its elastic domain. Suppose that a static loading is realized as a force applied along an axis (a stress) so as to stretch or compress (more generally, to strain) the system. Then response 1 means that the system as a whole undergoes a coordinate transformation that changes the distances between all the atomisms but not the topology of the system's internal configuration. This response to static loading is reversible. It is, however, a response of finite capacity. At some point the potential energy stored up within the excessively strained bonds reaches a limit (the elastic yield) and new mechanisms for accommodating the applied energy must be found (that is, a new "escapement" arises). One escapement mechanism is the breaking of some bonds between some atomisms (response 3), another escapement is diffusion (response 2) which is enhanced considerably by the structural changes resulting from bond breaking. (In a multiphase system at the elastic limit there is a structural change in at least one phase; for example, in the continuous solid phase of a two phase solid–fluid system such as a gel or in the more rigid phase of a polyphase solid–solid system such as a polycrystalline metal or a polyphase solid–fluid phase system such as a high polymer.)

A brittle system (a physical ideal, an engineering myth) would be infirmed at the elastic limit. There are no plastic deformations (flow processes) in a brittle system and microscopic bond breaking becomes, immediately, macroscopic fracture. For real, ductile systems, however, the yield point only identifies that loading at which fracturing begins on the atomistic level. Once the yield point is reached in a ductile system the mutually reinforcing processes of bond breaking and diffusion can continue to accommodate excessive energy brought in by the static loading. The dissociating of some of the atomisms makes it easier for other bound atomisms to migrate to locations that are more stable than the locations that they currently occupy. This flow process is irreversible: Less energy is required for an atomism to hop from a high to a low potential site than vice versa. However, the consequent relaxing of some bonds brought about by diffusion increases the strain on other, already overstrained, bonds, disposing them to further fracture.

The microfracturing that begins at and proceeds beyond the yield point reduces the long range order or cooperativity of the system (interpreted as bonds that repeat regularly over many thousands of atomic distances). The long range order is replaced by short range order or local cooperatives, not unlike the "flow unit" of a liquid. The diffusion occurs at the surface of these local clusters because the atomisms located there are thermally less stable than their partners in the interior. Clearly, the larger the number of local cooperatives and, therefore, internal surfaces, the greater the diffusion. And the greater the diffusion the more disposed to breaking are the already strained bonds at places in the system where diffusion of atomisms is not possible. In sum, fracturing of the bonds between atomisms is a chain reaction process and eventually a ductile system will fracture at the macroscopic scale.

The emphasis of the foregoing has been the gradual progression of macroscopic fracture, or system failure, as might occur under the repeated or prolonged application of static forces that exceed the system's elastic limit. In the range between the initiation of bond breaking on the microscale and the occurrence of system failure on the macroscale, the system gradually loses its ability to absorb the applied energy. A measure of the energy asorption of a material is given by its stress-strain curve, which relates force per unit area to proportional change in length. The energy per unit volume is approximately equal to the shaded area of Fig. 10.14. Consequently, the strain energy to failure may be approximated as follows: energy/unit volume = $\frac{1}{2}(P_x + \epsilon_x)P_c$. Where P_c is the stress at the yield point and P_x and ϵ_x are the ultimate stress and ultimate strain, respectively, that mark the collapse of the system.

Of course, the loss of ability to absorb energy could be quick, given a collision. The microscopic processes leading to failure from a single brief loading must be a rapid chain reaction of bond breaking associated with elastic and plastic waves propagating from the point of contact and multiply reflecting from the system's boundary. However, as noted, broad conclusions relating failure to the conditions of collision are possible without considering the complex of intermediary processes.

A collision will have an *acceleration* (of the system) × *time* profile. Three examples of single loadings are given in Fig. 10.15; to achieve a given response amplitude, shorter durations of loading must be compensated by greater accelerations. Two parameters are of special significance: the change in velocity and the average acceleration (in units of gravity) that is *just sufficient to produce structural failure*. In Fig. 10.15 the cross-hatched areas express the velocity changes. The average acceleration of any collision is equal to the velocity change divided by duration. A collision sensitivity curve can be generated by plotting criterial velocity change (where fracture occurs) against criterial average acceleration (where fracture occurs) (Kornhauser, 1964). A prototypical collision sensitivity plot is given in Fig. 10.16. The vertical asymptote is related to acceleration pulses that are steady or of long duration. It implies that no failure occurs unless a certain average acceleration is exceeded, regardless of the change in velocity of the system and the duration of the collision. The horizontal asymptote is related to acceleration pulses of short duration. It implies that system failure does not

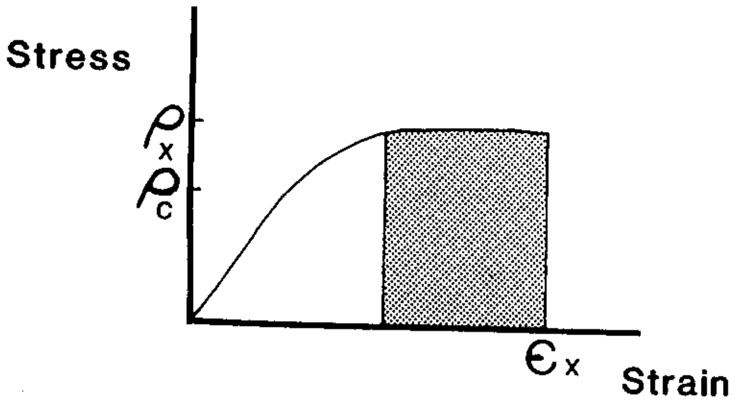

FIG. 10.14. The energy absorption per unit volume of a material is given by the shaded area of its stress-strain curve.

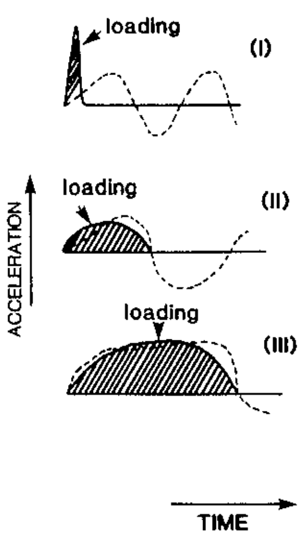

Fig. 10.15. *Acceleration* × *time* profiles of collisions under three loading durations (after Kornhauser, 1964).

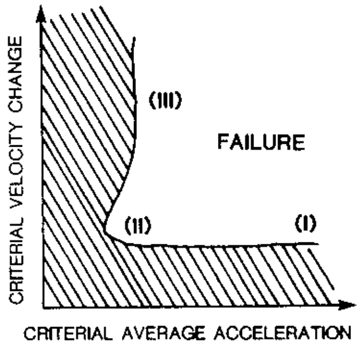

FIG. 10.16. Collision sensitivity plot shows where system failure will occur (after Kornhauser, 1964).

occur unless a certain velocity change is exceeded regardless of the average acceleration value (Kornhauser, 1964).

The location of the vertical asymptote in Fig. 10.16 is a function of the shape of the collision (its *acceleration* × *time* profile). In contrast, the horizontal asymptote is independent of the shape of the loading and is fully characterized by a unique value of velocity change: Collision durations that are short enough to be on the short duration asymptote (marked by (I) and (II) for a given system will result in the structural failure of that system. There is some evidence (Kornhauser, 1964) to suggest that the collision velocity change required for irreversible damage to mammals is relatively indifferent to species and size (25 feet per second is a reasonable approximation). The criterial average acceleration, however, differs markedly with species and size (roughly, 20 g for man and 650 g for mice).

A simple rule of thumb relates the critical velocity change (V_c) and criterial average acceleration (G_c) to the system's natural frequency (ω) (Kornhauser, 1964): $G_c = \omega V_c$. If most collisions between systems and their surrounds are of sufficiently short duration to place the systems on the horizontal asymptote of their collision sensitivity function, then V_c is constant. (For mammals, as noted previously, $V_C = 25\ f/s$.) In other words, the higher the value of a system's natural frequency, the greater is the system's tolerance to collision (measured in multiples of the gravitational constant).

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