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Imagine a crystalline world of tiny, discrete "cells", each knowing only what its nearest neighbors do. Each volume of space contains only a finite amount of information, because space and time come in discrete units. In such a universe, we'll construct analogs of particles and fields -- and ask what it would mean for these to satisfy constraints like conservation of momentum. In each case classical mechanics will break down -- on scales both small and large, and strange phenomena emerge: a maximal velocity, a slowing of in

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20. Internal clocks, a bound on simultaneous measurement, and quantum-like effects in very weak, or intense fields.

This fantasy about conservation in cellular arrays was inspired by this first conference on computation and physics, a subject destined to produce profound and powerful theories. I wish this essay could include one such; alas, it only portrays images of what such theories might be like. The "cellular array" and Von Neumann's work on self-producing machines. This essay exploits many unpublished ideas I got from Edward Fredkin. The ideas about field and particle are original; Richard Feynman persuaded me to consider fields instead of forces, but is not responsible for my compromise on potential surfaces. I also thank Danny Hillis and Richard Stallman for other ideas.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ARTIFICIAL INTELLIGENCE LABORATORY

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NATURE ABHORS AN EMPTY VACUUM

Marvin Minsky

ABSTRACT: Imagine a crystalline world of tiny, discrete "cells", each knowing only what its nearest neighbors do. Each volume of space contains only a finite amount of information, because space and time come in discrete units. In such a universe, we'll construct analogs of particles and fields -- and ask what it would mean for these to satisfy constraints like conservation of momentum. In each case classical mechanics will break down -- on scales both small and large, and strange phenomena emerge: a maximal velocity, a slowing of internal clocks, a bound on simultaneous measurement, and quantum-like effects in very weak or intense fields.

This fantasy about conservation in cellular arrays was inspired by the first conference on computation and physics, a subject destined to produce profound and powerful theorems. I wish this essay could include one such; alas, it only portrays images of what such theorems might be like. The "cellular array" idea is popular already in such forms as Ising models, renormalization theories, the "Game of Life" and Von Neumann's work on self-producing machines. This essay exploits many unpublished ideas I got from Edward Fredkin. The ideas about field and particle are original. Richard Feynman persuaded me to consider fields instead of forces, but is not responsible for my compromise on potential surfaces. I also thank Danny Hillis and Richard Stallman for other ideas.

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NATURE ABHORS AN EMPTY VACUUM

Marvin Minsky

Could any universe satisfy these two conditions?

> Each volume of space contains only a finite amount of information, because space and time come in discrete units.

> Over some range of size and speed, the mechanics of this world are approximately classical.

Imagine a crystalline world of tiny, discrete "cells," each knowing only what its nearest neighbors do. In such a universe, we'll construct analogs of particles and fields, and ask what it would mean for these to satisfy constraints like conservation of momentum (1). [illegible]

[illegible]

[illegible]

[illegible]

t=0	•	•	•	1	1	1	1	P	•	•	•	•	•
1	•	•	•	1	1	1	P	P	•	•	•	•	•
2	•	•	•	1	1	P	P	P	•	•	•	•	•
3	•	•	•	1	P	P	P	P	•	•	•	•	•
4	•	•	•	•	P	P	P	P	•	•	•	•	•
5	•	•	•	•	Q	P	P	P	•	•	•	•	•
6	•	•	•	•	1	Q	P	P	•	•	•	•	•
7	•	•	•	•	1	1	Q	P	•	•	•	•	•
8	•	•	•	•	1	1	1	Q	•	•	•	•	•
9	•	•	•	•	1	1	1	1	P	•	•	•	•

SIZE AND PRECISION. In this example, the size of a packet is inverse to its speed. In general, there is an absolute constraint between the amount of information in any packet and the volume of that packet! And, [illegible] Heisenberg's principle, it is not so much a parameter's value that determines packet size, as its [illegible] the number of "bits of information" needed to specify it. [3]

[illegible] information carried in a packet were "optimally encoded" — in accord with Shannon's information [illegible] the packet's size would depend on the Base-2 logarithm of its precision. Then why is there no [illegible] Heisenberg's principle? We'll conjecture that most physical information (particularly in [illegible] not in Base 2 but in the less dense Base-1 form. Later we'll argue that particles with [illegible] display distinct colors! [4]

[illegible] we can prove that any isolated packet which moves within a regular lattice must [illegible] helical trajectory. Such trajectories will appear perfectly straight on any large enough [illegible] deduce Newton's law of inertia (for compact particles) directly from the regularity of the [illegible] [5]

[illegible] than the basic lattice speed of one cell per [illegible] largest possible speed. We [illegible] with the Speed of Light. It is easy to design [illegible] using simple rules [illegible] each cell's state into a neighbor more [illegible] with lightspeed propagation. There are fundamental differences between lightspeed [illegible] photons [illegible] a photon's wavefront can never [illegible] the information [illegible] simple [illegible] cannot do three [illegible] computation [illegible] that they can't compute enough to [illegible]

[illegible] computational [illegible] back and forth through some [illegible] at (N-1)/N [illegible] at least (N-1) moments for data [illegible] the order of N. Therefore the [illegible]

[illegible] different frames and [illegible] special [illegible] with different [illegible]

ANGLE and APERTURE. In real optics it takes *twice* the aperture, for any given wavelength, to halve a beam's divergence -- while "optimal" encoding of the angle should only need a single extra "bit" -- another hint that nature uses "Base-1" codes for photons -- perhaps because only Base-1 codes could let a discrete mechanism "add" fast enough to make things linear at lightspeed. {6}.

FREQUENCY AND TIME. The angular precision of a real photon depends only on how many wavelengths cross the aperture. So one can keep a beam's shape fixed while shrinking aperture and wavelength both -- and that must mean the wavelength information must be stretching longitudinally -- just as implied by the energy-time form of Heisenberg's principle. {7).

II. -------- SPHERICAL SYMMETRY

No regular lattice is invariant under rotation, Euclidean or Lorentz, since it needs different information to move along different axes so, just as waves in crystals show Bragg diffraction, "discrete vacuums" must show angular anisotropies (that might reveal themselves on some small scale of size or extreme energy). But we won't touch such problems here -- because I feel they've deflected almost everyone from more important, finite things! Physics has to face some day those problems anyway -- of finite geodesic, differential, and isotropy, because (I'll argue) they already lurk beneath the surface of our modern theories. But here our main concern is seeing how a discrete world could have some other ordinary properties on ordinary scales. We'll just note several possibilities. {8}.

LIQUID LATTICE MODEL. One could imagine cell connections so randomly irregular that, in the large, the space is isotropic -- like water, which is almost crystalline *from* each atom to the next, but isotropic on the larger scale. But then, to build our packets into such a world, we'd have to find transition rules insensitive to local cell-connection fluctuations.

CONTINUOUS CREATION. Instead of starting with a liquid vacuum, we could randomly insert new cells from time to time. This would cool and redshift cosmically old photons (by lengthening their unary frequency counters) and uniformly expand the universe. But, again, it would be hard to design things to survive such changes without changing.

SPHERICAL PROPAGATION. So little is known about approximating isotropic propagation in regular lattices that we can only pose some problems:

1. *Describe a cellular array in which local disturbances cause asymptotically spherical expanding wavefronts.* I don't think much would come from seeking this in finite difference equations, because one must bound the variables. One can invent constructions that slowly grow increasingly spherical polygons -- but a solution of physical interest must propagate at lightspeed. The next section suggests doing this with an "exchange particle" mechanism. I suspect some such technique may be necessary -- physically to transfer information from one place to another, to maintain long-range metric constraints.

2. *Describe a cellular array in which "particles" exert inverse square forces on one another, with only light-speed delay.* Such issues concerned physics long before relativity, but "ether" theorists never found good solutions. One idea was for particles continuously to emit force-waves that increment other particles' momenta. But then the information content of such waves would grow as their intensities decay -- and that would be incompatible with any bound on information density. {10}.

FORCE STREAMS. Making each particle emit showers of randomly oriented "force pellets" solves both inverse-square and weak-field information problems. But it leaves a probably equivalent problem of how each particle could approximate a uniform spherical distribution of its pellets. Another variation fills the universe with a gas of light-speed momentum pellets whose "shadows" cause inverse-square forces. This transfers the isotropy burden to the universe as a whole. Unfortunately (according to Feynman [Ref. 1]) this too quickly drags everything to rest within the distinguished inertial frame of that isotropy. {8}.

CURVATURE. Suppose a spherical force field were known to have emerged from a "unit charge". Now represent that field by marking space itself as a family of equipotential surfaces. These markings need no further local information at all, because the field intensity at any point can be determined just from local curvature. The trouble is, for such a field to act on any particle, the particle will have to to find that curvature -- and when that curvature is very small, the particle must probe great distances. How, then, could any particle respond as though the interaction works at lightspeed? We have an answer, shortly.

III. -------- FIELDS

The idea of field abandons that of force, and only asks the vacuum to constrain some local quantity. This promises to reduce information density, just as a single differential equation replaces infinite summations in Huyghen's principle. It might seem natural to start applying difference equations (instead of the partial differential equation of physics) to discrete quantities (instead of continuous vector fields). But that won't work for us, because it needs precision beyond bound -- which would make the computations take so long there'd be no link between causality and speed of light. {9}.

"Action at a distance" was solved by fields -- by writing nature's laws in differential form. But what of "action at a differential distance"? Modern theories still assume that nature can use methods that are infinitely rapid and precise. (When wave-equations specify relations between partial derivatives, how can the vacuum measure and compute those "informational infinities".) To be sure, a discrete theory asks its cells to acts upon their neighbors. But there, where distance is itself *defined* in terms of "that which interacts" it's really quite a different kind of question.

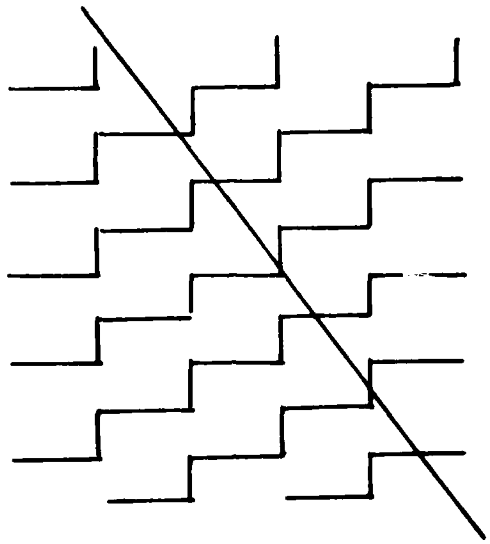
We've all become so comfortable with "real" numbers that we've come to think they're really real -- and then we grumble when our theories give us series that make us pick and choose which terms to keep or throw away! I'll argue that the finite view might show us how to make such choices. But let us set philosophy aside and try to make mechanics come directly from the field, avoiding all derivatives and real numbers. We'll try a scheme in which the state-change laws control a family of surface, to operate directly on the field's "shape".

MECHANISM I: FIELD AS SURFACE WITH EXCHANGE FORCE

Consider now a classical potential field. To represent the field, we'll simply "mark" those vacuum cells that happen to be near some closely-spaced potentials. {11}. Then to obtain mechanics, the structure needs a way to act on charge: each time a particle crosses a surface it adds, to its kinetic energy, a unit vector normal to that surface. This

(i) eliminates the need for a local gradient computation
(ii) simplifies interactions for the particle.
(iii) permits light-speed reactions on the field.

How could a particle compute that surface normal without having to pause for lateral exploration? A trick: since equipotential surfaces are nearly parallel, the particle can make the exploration as it moves along its proper trajectory! This is because each surface, in this discrete space, is locally composed of polygons -- that *separately* supply components as the particle goes through!



Each surface micro-polygon is normal to a lattice axis, so the particle need only add a unit scalar constant to its kinetic energy component along that axis. This solves the particle's derivative problem.{12}. But how can the field maintain those surfaces? Some sort of local "force" must work to move them in accord with the Laplacian,

$$\frac{d}{dx}\left(\frac{d\Phi}{dx}\right) + \frac{d}{dy}\left(\frac{d\Phi}{dy}\right) + \frac{d}{dz}\left(\frac{d\Phi}{dz}\right)$$

so some physical activity must represent the information in *those* derivatives. We now propose only a sketchy "approach" to this, hoping the reader won't be upset when left in hopeless tangles of loose ends. We'll fill the vacuum with a gas of light-speed "exchange" photons -- call them "ghotons" -- that bounce between, and push apart adjacent surfaces. A perfect gas won't do, because the "pressure" must depend on local distance between surfaces -- so we'll give every X-surface element an X-ghoton, to bounce between that surface and the next, and same for Y and Z. (To ensure a single ghoton for each oriented surface element, each element emits ghotons continually -- but returning ones annihilate the ones they meet.)

The field intensity components $Fx = d\Phi/dx$, etc., are inverse to the axial projections of the intersurface distances. Hence each x-surface element sees one reflected photon each $2/Fx$ moments. Therefore the impact frequency is proportional to Fx -- and the "vector pressure" is proportional to the field's gradient. So the difference from both sides is

$$\frac{d}{dx}\left(\frac{d\Phi}{dx}\right) \cdot \frac{d\Phi}{dx}$$

This shows how differentials can emerge, in spite of local finiteness, by using "exchange forces". My intuition is that even if mechanics were continuous -- but still had information limitations, some process like "exchange" would still be needed. (The extra factor $d\Phi/dx$ could be taken out, by ghoton-counting tricks, but actually it cancels anyway when Maxwell's scalar equation is re-written in terms of surface motion rather than potential change at a point. Would this reveal a fatal flaw because, when weak fields change, the surfaces must move faster than light?)

To realize the wave equation, the ghotons must cross-interact so as make the Laplacian sum *accelerate* the potential -- but I don't see exactly how to do this. If each surface of an analogous family of *continuous* surfaces were to emit ghotons in proportion to area, the pressures would be in equilibrium when the intersurface spacings are just like those of a Coulomb field with the same curvature. But it looks hard to make a discrete version of that, and I'll only mention some of the problems.

The wave equation's second time derivative means velocity must be represented, not just position -- we'd need to, anyway, for representing field momentum. There's room enough because both gas and surface elements are one-dimensional (velocity could be coded into ghoton-trains). We also need machinery to keep the surfaces smooth -- perhaps by some exchange *inside* the surfaces. Surely the whole thing must be done with a vector potential. Best of all would be to find a way to do without those surfaces at all, to leave the field as nothing but a cloud of interacting ghotons -- from which particles could directly draw momentum, as Robert Forward pointed out to me. {13}.

Given so many problems, is the subject worth pursuit? I think it is because our present theories have such weak foundations. We tend to view (for instance) terms of Feynman diagrams as mere approximations -- because we see them as low-order terms of power series. Our finite information theory hints, instead, that those exchange devices are what's really real -- because there must be something physical to transfer information. And then (oh, joy) those scary analytic integrals become the artifacts -- originating from the error of continuous approximation to something that by nature is discrete!

MECHANISM 2: INTERACTIONS BETWEEN DISPERSED QUANTITIES

How could two packets ever interact, if information is dispersed in space? Consider a collision between two bodies A and B whose momentum information is very precisely specified -- hence very large in size. In classical physics momentum is itself distributed, and in quantum theory its probability amplitude. But in a discrete theory what is dispersed is neither momentum itself -- nor its probability -- but the information that defines it. This gives the problem a different character, one of *access* to information. What happens when "A reaches B", if some of B's momentum information lies halfway across the galaxy?

If A must "know" the farthest fringe of B's momentum-data, the interaction must be delayed -- confirming neither classical nor quantum expectation. It seems to me there's just one way a discrete vacuum could approximate a classical collision: by "estimating" the dispersed particles' momenta. In order that they interact at all, the particles must work with less than all the information classically required. So now we'll sketch a scheme for prompt, conservative interaction that doesn't achieve all its goals, but illustrates again how discrete models lead to quantum-like phenomena. We shall assume that if A and B interact it is because

> 2a. At some space-time locus an "event" occurs in which the incoming particles' momenta are "estimated", and the outgoing momenta are determined by applying classical rules to these estimates. {14}.

Because of estimation errors, the scattered momentum sums need not exactly equal the initial sums, so we need an "error conservation" mechanism:

> 2b. Each scattered particle leaves a "receipt" with the other, recording how much momentum was actually removed. The "event locations" of (2a) are the receipts from previous interactions, because they contain information needed to estimate the new "real" momenta.

We shall assume further that

> 2c. The new trajectories are determined only by the "estimates"; the receipts go along invisibly until combined into subsequent interactions.

It might well seem more logical for "receipt" momentum to continuously cancel, between interactions, against "observable" momentum. However that would violate least action, producing interference patterns corresponding to curved trajectories.

If we combine mechanics in this way with unobservable receipts, deterministic systems show some qualitative features that resemble quantum, mixed-state systems. Thus one can always measure the "real" momentum in Event 1 by the location of Event 2. But one cannot yet "observe" the "receipt" momentum of Event 1, because it is not until Event 2 that it first combines with any "real" momentum -- which cannot be "observed" until some subsequent Event 3 -- by which time it is already mixed with another estimate! And so on. One can never simultaneous measure both estimates and receipts, though all adds up eventually. And all this involves no probabilities at all, just temporary inaccessibility of information!

Estimates and receipts also permit tunneling -- interactions that involve more momentum than available. All is repaid when receipts eventually return their information in new estimates, but every particle at every moment carries some invisible receipts not measured yet. The model can even show some qualitative features of quantum interference; if ever two particles were involved in the same interaction, they can share identical receipt information that gives them some coherent, "same random" properties in later interactions. Perhaps *any* information-limited mechanism for conservation and fast interaction needs some such two-part scheme.

Could anything like this yield "correct" quantum mechanics? Almost surely not, since that would solve the "hidden variable" problem -- which probably has no solution under lightspeed limitations. (Without that limitation, one might imagine ways to make the invisible receipts diffuse ergodically between interactions gathering information; and using that to control the distribution of events. But that exploration would have to proceed arbitrarily much faster than light -- and it would not help to appeal to an ensemble of similar situations, since some needed information lies outside the relevant light-cone.) It's hard to lose causality, but better to face facts. {14}.

MECHANISM 3: PARTICLES AS PRODUCTS OF VACUUM SATURATION

Why do we have particles with rest mass? I'll argue that they're needed to conserve fields! We have supposed that fields use *Base-1* in order to be fast. What happens when a field gets so intense that (in our surface model) neighbor planes are forced together? Must then information be destroyed? No, because there's a loophole: we can provide that at some certain threshold of intensity, the vacuum state rules change things to a coding that is more compact -- e.g. Base-2. That must sound silly, but [illegible]

To be concrete, we go back to that field-surface representation, and propose that: *when field-surfaces are forced into contact, they are replaced -- in pieces -- by "Base-2 abbreviations".* Now, this "abbreviation" process must be almost instantaneous, or else the threatened information will be permanently lost. But then the lightspeed limitation means that this "abbreviation" can't depend on much! So we "deduce" that

3a. *Each "abbreviation" replaces a standard unit of field.*

Since the locally compressed surfaces are nearly parallel, we need only to record a single spatial orientation:

3b. *Each "abbreviation" contains a single unit direction vector.*

Perhaps this is why "spin" comes in absolutely standard units. The potential energy of the compressed field must also be recorded -- and (3a) means that its magnitude is a fixed "quantum".

3c. *"Abbreviations" carry fixed amounts of potential energy.*

The surfaces of squashed, time-dependent, fields also contain momentum to be conserved:

3d. *Each "abbreviation" carries a (variable) momentum vector.*

If the energy encoded in these "abbreviations" is ever to interact again, or even to decay back to field, they'll need to be able to do some computation, hence

3e. *"Abbreviations" must move at less than lightspeed.*

These properties so unmistakably resemble particles with *rest mass* that we conjecture:

Particles with rest mass are compressed, densely-encoded representations of fragments of unary-coded fields.

Since the rest mass corresponds to the potential energy drawn from the field in (3c), the velocity of (3e) is determined by the momentum drawn from the field in (3d). Thus we "deduce" (without relativity[1]) that if energy and momentum are conserved throughout, then

3f. *A particle's rest mass is proportional to the potential energy of the field consumed to create it.*

So in this fantasy it is purely to preserve energy and momentum of strong fields that we must suffer the creation of particles -- because conversion to more compact information code is the only way to conserve information. The resulting "abbreviations" must move slowly and act slowly. They must act strangely too, because we cannot keep re-using that stratagem of extending conservation by re-coding. To be sure, there are many encodings intermediate between Base 1 and Base 2; the latter are the most compact possible codes. The closer the encoding approaches that ultimate density, the fewer ways remain for different particles to share the same space -- so we must see either stronger exclusion rules or more interactions in which particle identities are changed or lost entirely. So we can conclude, at least qualitatively, that

3g. *Particles with rest mass have strong, short-range forces.*

[1] [illegible] information [illegible] [15]. [illegible] conservation of energy has [illegible] down

that road:

3h. *Particle creation cannot conserve all of a field's topology.*

This is because a Base-2 particle moves slower than its field *and* takes time to "decay". Therefore, when it returns its information to its field, this will happen at some remote "wrong" place -- so the global configuration of the field will have been changed. We speculate next that properties like *charge* amount to imperfect attempts to conserve the originating field's topology.

MECHANISM 4: CONSERVATION AND TOPOLOGY

What happens to the torn edges of those disrupted surfaces? Could one simply remove [illegible] equipotential? (Physically, the idea seems nonsensical -- but we'll ignore that.) Topologically, removing [illegible] potential shells would seem equivalent to creating dipole pairs of charge. So making charges can [illegible] topology" provided that (i) they're made in pairs and (ii) they carry charge fields like the fields [illegible] came from. To the extent that charges represents abbreviated topology, one would certainly expect [illegible] charges never vanish.

Can we pursue this down to the very lattice elements? Mechanism 3h argues that a "unit vector [illegible] abbreviate the surface normal of the collapsing field. But at lattice resolution there are no unit vectors [illegible] microscopic collisions between axis-parallel "field-surface polygons". These have three axis-symmetry classes each with eight different signed ways that dihedral edges can meet surfaces (and other ways for [illegible] edges to collide). Abbreviating any such event replaces some local field configuration by [illegible] oriented A(xis)-O(bject).

Each such sub-elementary event creates a pair of these AO's, and each must soon be joined by [illegible] the other axes -- but those may be quite far away, depending on the field's direction cosines. [illegible] scarcely imagine creating an observable particle from a single AO -- with its single-axis scalar [illegible] better to wait until enough AO's combine to make a "genuine" momentum vector. How might [illegible] find their complements? The simplest scheme would keep each AO attached to its disrupted [illegible] propelled by unbalanced ghotons until another is encountered, then a "2/3 AO" is formed. If two [illegible] one axis will be twice represented -- so the two of them must wait to cancel with an appropriate [illegible] and so forth. Of course that "so forth" is pure bluff; I've said too much already, and real physicists [illegible] of better reasons why and how sub-elementary particles must be bound by unobservably large forces.

IV. ------- SUMMARY AND CONCLUSION

We started with the idea that in a cellular array, no field can work at lightspeed except with [illegible] information codes. We found that to approximate a Coulomb field needs something like an exchange force. Finally we saw that "Base-2" things with "rest mass" must emerge from suitably intense fields -- just to conserve information before it's squeezed to death. So, starting with a simple, finite field idea, we ended with a cluttered world of sluggish, complicated objects with queer interactions, internal structures, exclusion rules and short-range forces.

Conservation also caused "uncertainty" to invade our simple world, because the local finiteness requires that all information be dispersed. To make fast interaction possible at all, and conservation too, something must keep the books -- and we proposed a complicated system of "events", "receipts" and "estimates". Are there much simpler schemes that permit both exact conservation and lightspeed interaction? The present schemes, though incomplete, seem too complex already.

[illegible]

[illegible]

[6 Wavefronts] Growth of the sidelobes of diverging beams can be controlled by "interference" from the beams' interiors, because oblique contributions from the front can meet less oblique contributions from inside. But information can move directly forward, only when portions of the front "hesitate". If that happens periodically the group velocity falls below C, and there's no photon. But for expanding waves, which grow asymptotically planar, the totality of such delays can be bounded to a finite delay (or phase shift) in each direction.

[7 Energy and Time] For a diffraction slit, anyway. For a circular aperture something's wrong, because halving the diameter should make the information stretch *four* times further along time where the uncertainty principle has only a factor of two.

[8 Relativity] The discrete lattice does imply an absolute kinematic frame, and an absolute distinction between space and time. One cannot quarrel with relativity; still, from an informational view it is hard to see how physics could be entirely independent of frame: the information must be somewhere to represent each [illegible]. And while no physics theory can stand, that lacks Lorentz invariance on ordinary scales, still no one [illegible] what happens at the ultimate extremes.

[illegible] measured redshift measurements of the primordial microwaves might show us one distinguished [illegible] frame. [illegible] could argue that this does not violate equivalence because it's easy to shield [illegible] from microwaves. Suppose, though, that some later day reveals the redshifts of the oldest [illegible] then shielding is unthinkable. And two observers in their different frames must truly find some [illegible] different measures for those rays. Most likely, though, we'll never [illegible] will one wonders if that old [illegible] of relativity could reach that far?

[illegible] it's hard to avoid the idea that if the expansion of the universe is to locally increase the space between points, it is hard to avoid the idea that the number of cells in the volume must increase, [illegible] acceptable because one can hardly change the number of [illegible] in a lattice.

[illegible] It would [illegible] for weak fields simply to vanish below a certain threshold. [illegible] sparse information distributions then conservation can be [illegible] quantized rather than continuous.

[illegible] What [illegible] might the lattice have? If adjacent potentials differed by 10^{20} [illegible] If we put 10^{20} cells between such surfaces (for room to [illegible]) we'd end up with the order of 10^{40} cells across a nucleus if nothing changed down [illegible] But things do change there [illegible] we later argue that things like protons exist *because* that [illegible] for ordinary fields to work! So halfway in between might do, say, 10^{30}.

[illegible] Added in proof: The construction above is incorrect because the cross-section for the different [illegible] depends on the particle's incidence angle. The correct components might be [illegible] by measuring the distance within each surface, to the first "step" in each axial direction. But that takes time and might not be compatible with fast interaction.)

[illegible] change a particle's velocity when making unit increments to its particle's kinetic [illegible] kinetic energies as squares *literally!* [illegible] so that velocity is an [illegible] cubic lattices. In any case, it would seem easier [illegible]

[13: Energy]. The surface-ghoton impact rate is proportional to the field's potential energy density. (The impact rate per surface element is proportional to field intensity, and so is the number of surface elements per unit volume. Hence the impact density scales with energy.) This could produce a space curvature proportional to energy -- if every ghoton-photon event caused the photon to hesitate for a moment! Could some analogous processes yield spacetime curvature?

[14: Events]. It certainly seems unlikely that there is any way to define deterministic "events" to be consistent with quantum facts. (Some might prefer alternatives with no "events" at all, as in a quantum theory with amplitudes but no probabilities, but then we must suffer the dreadful spectre of Schrodinger's cat.) Perhaps it might still be possible to approximate the standard view (in which "observations" replace mixed states by pure states) in discrete models with symmetrical past-future state-change rules -- i.e., with bidirectional causality. The basis of this thin conjecture is just that this permits global constraints to hold in spacetime regardless of lightspeed limits, hence opens again the hidden variable problem.

It might be worth exploring "discrete phase" models in which states can cycle through some large but finite group of phases. Then one should obtain some "all possible paths" phenomena, and interesting kinds of interference. A remarkably simple example of such an array, that can "self-reproduce" arbitrary spatial patterns at remote locations, was discovered by Fredkin and described in [Ref. 4].

[15: Reversibility]. That is, unless the basic state rules themselves are reversible. Fredkin has shown local time-reversibility to be compatible with many cellular array computations, and it would certainly seem of physical interest to consider time-reversible vacuum-state rules, for in some sense they would conserve everything. [Ref. 5].

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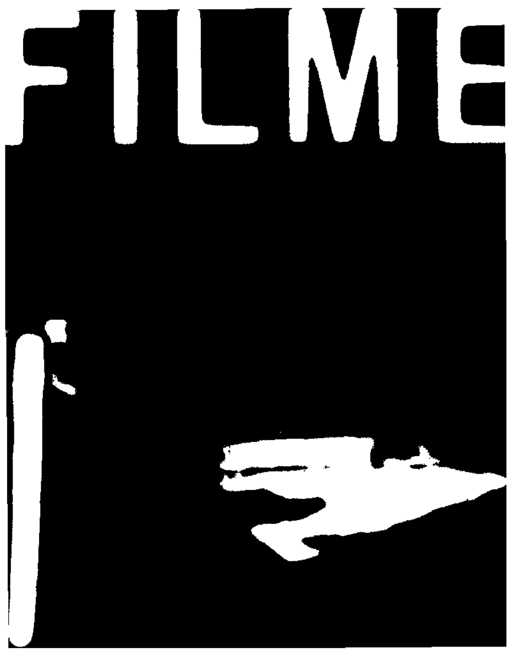
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