Animation of Plant Development

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ABSTRACT

This paper introduces a combined discrete/continuous model of plant development that integrates L-system-style productions and differential equations. The model is suitable for animating simulated developmental processes in a manner resembling time-lapse photography. The proposed technique is illustrated using several developmental models, including the flowering plants *Campanula rapunculoides*, *Lychnis coronaria*, and *Hieracium umbellatum*.

CR categories: F.4.2 **[Mathematical Logic and Formal Languages]**: Grammars and Other Rewriting Systems: *Parallel rewriting systems*, I.3.7 **[Computer Graphics]**: Three-Dimensional Graphics and Realism: *Animation*, I.6.3 **[Simulation and Modeling]**: Applications, J.3 **[Life and Medical Sciences]**: Biology

Keywords: animation through simulation, realistic image synthesis, modeling of plants, combined discrete/continuous simulation, L-system, piecewise-continuous differential equation.

1 INTRODUCTION

Time-lapse photography reveals the enormous visual appeal of developing plants, related to the extensive changes in topology and geometry during growth. Consequently, the animation of plant development represents an attractive and challenging problem for computer graphics. Its solution may enable us to retrace the growth of organs hidden from view by protective cell layers or tissues, illustrate processes that do not produce direct visual effects, and expose aspects of development obscured in nature by concurrent phenomena, such as the extensive daily motions of leaves and flowers. Depending on the application, different degrees of realism may be sought, ranging from diagrammatic representations of developmental mechanisms to photorealistic recreations of nature's beauty.

Known techniques for simulating plant development, such as L-systems [16, 27, 28, 31], their variants proposed by Aono and Kunii [1], and the AMAP software [4, 10], operate in discrete time, which means that the state of the model is known only at fixed time intervals. This creates several problems if a smooth animation of development is sought [27, Chapter 6]:

- Although, in principle, the time interval can be arbitrarily small, once it has been chosen it becomes a part of the model and cannot be easily changed. From the viewpoint of computer animation, it is preferable to specify this interval as an easy to control parameter, decoupled from the underlying model.
- The continuity criteria responsible for the smooth progression of shapes during animation can be specified more easily in the continuous time domain.
- It is conceptually elegant to separate the model of development, defined in continuous time, from its observation, taking place in discrete intervals.

Smooth animations of plant development have been created by Miller (a growing coniferous tree [19]), Sims (artificially evolved plant-like structures [30]), and Prusinkiewicz *et. al.* (a growing herbaceous plant *Lychnis coronaria* [24]), but the underlying techniques have not been documented in the literature. Greene proposed a model of branching structures [12] suitable for animating accretive growth [11], but this model does not capture the non-accretive developmental processes observed in real plants.

This paper introduces a mathematical framework for modeling plants and simulating their development in a manner suitable for animation. The key concept is the integration of discrete and continuous aspects of model behavior into a single formalism, called *differential L-systems* (dL-systems), where L-system-style productions express qualitative changes to the model (for example, the initiation of a new branch), and differential equations capture continuous processes, such as the gradual elongation of internodes.

The proposed integration of continuous and discrete aspects of development into a single model has several predecessors.

Barzel [2] introduced *piecewise-continuous ordinary differential equations (PODEs)* as a framework for modeling processes described by differential equations with occasionally occurring discontinuities. PODEs lack a formal generative mechanism for specifying changes to system configuration resulting from discrete events, and therefore cannot be directly applied to simulate the development of organisms consisting of hundreds or thousands of modules.

Fleischer and Barr [7] addressed this limitation in a model of morphogenesis consisting of cells developing in a continuous medium.

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The configuration of the system is determined implicitly by its geometry. For example, in a simulated neural network, a synapse is formed when a growing dendrite of one cell reaches another cell.

Mjolsness *et. al.* [21] pursued an alternative approach in a *connectionist model of development*. Differential equations describe the continuous aspects of cell behavior during interphase (time between cell divisions), while productions inspired by L-systems specify changes to the system configuration resulting from cell division and death. The connectionist model makes it possible to consider networks with arbitrary topology (not limited to branching structures), but requires productions that operate globally on the entire set of cells constituting the model. This puts a practical limit on the number of components in the system.

Fracchia *et. al.* [9] (see also [27, Chapter 7]) animated the development of cellular layers using a physically-based model in which differential equations simulate cell growth during the interphase, and productions of a *map L-system* capture cell divisions. The productions operate locally on individual cells, making it possible to simulate the development of arbitrarily large layers using a finite number of rules. Unfortunately, this technique does not seem to extend beyond the modeling of cellular layers.

Timed L-systems [27, Chapter 6] were introduced specifically as a formal framework for constructing models of branching structures developing in continuous time. They operate under the assumption that no information exchange between coexisting modules takes place. This is a severe limitation, as interactions between the modules are known to play an important role in the development of many plant species [14, 27, 28]. A practical application of timed L-systems to animation is described by Noser *et. al.* [22].

The model of development proposed in this paper combines elements of PODEs, the connectionist model, and L-systems. The necessary background in L-systems is presented in Section 2. Sections 3 and 4 introduce the definition of differential L-systems and illustrate it using two simple examples. Section 5 applies combined discrete/continuous simulation techniques to evaluate dL-systems over time. Section 6 focuses on growth functions, which characterize continuous aspects of model development. Application of differential L-systems to the animation of the development of higher plants is presented in Section 7, using the models of a compound leaf and three herbaceous plants as examples. A summary of the results and a list of open problems conclude the paper.

2 L-SYSTEMS

An extensive exposition of L-systems applied to the modeling of plants is given in [27]. Below we summarize the main features of L-systems pertinent to the present paper.

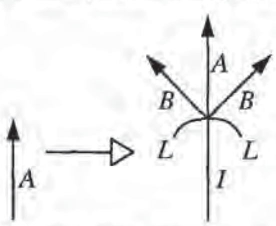

Figure 1: Example of a typical L-system production

We view a plant as a linear or branching structure composed of repeated units called *modules*. An L-system describes the development of this structure in terms of *rewriting rules* or *productions*, each of which replaces the *predecessor* module by zero, one, or more *successor* modules. For example, the production in Figure 1 replaces apex A by a structure consisting of a new apex A, an internode I, and two lateral apices B supported by leaves L.

In general, productions can be *context free* and depend only on the replaced module, or *context-sensitive* and depend also on the neighborhood of this module. A *developmental sequence* is generated by repeatedly applying productions to the consecutively obtained structures. In each step, productions are applied in parallel to all parts of the structure obtained so far.

The original formalism of L-systems [16] has a threefold discrete character [17]: the modeled structure is a finite collection of modules, each of these modules is in one of a finite number of states, and the development is simulated in discrete derivation steps. An extension called *parametric L-systems* [25, 27] increases the expressive power of L-systems by introducing a continuous characterization of the module states. Each module is represented by an identifier denoting the module *type* (one or more symbols starting with a letter) and a *state vector* of zero, one, or more numerical *parameters*. For instance, $M = A(5, 9.5)$ denotes a module M of type A with two parameters $w_1 = 5$ and $w_2 = 9.5$, forming the vector $\mathbf{w} = (5, 9.5)$. The interpretation of parameters depends on the semantics of the module definition, and may vary from one module type to another. For example, parameters may quantify the shape of the module, its age, and the concentration of substances contained within it.

Figure 2: Turtle interpretation of a sample string

In the formalism of L-systems, modeled structures are represented as *strings* of modules. Branching structures are captured using *bracketed* strings, with the matching pairs of brackets [and] delimiting branches. We visualize these structures using a *turtle interpretation* of strings [23, 28], extended to strings of modules with parameters in [13, 25, 27]. A predefined interpretation is assigned to a set of reserved modules. Some of them represent physical parts of the modeled plant, for example a leaf or an internode, while others represent local properties, such as the magnitude of a branching angle. Reserved modules frequently used in this paper are listed below:

$F(x)$	line segment of length x,
$+(\alpha), -(\alpha)$	orientation change of the following line by $\pm\alpha$ degrees with respect to the preceding line,
$@X(s)$	a predefined surface X scaled by the factor s.

The interpretation of a string of modules proceeds by scanning it from left to right and considering the reserved modules as commands that maneuver a LOGO-style turtle. For example, Figure 2 shows the turtle interpretation of a sample string:

$$F(1)[+(45)@L(0.75)]F(0.8)[-(30)@L(0.5)]F(0.6)@K(1),$$

where symbols $@L$ and $@K$ denote predefined surfaces depicting a leaf and a flower.

3 DEFINITION OF dL-SYSTEMS

Differential L-systems extend parametric L-systems by introducing continuous time flow in place of a sequence of discrete derivation steps. As long as the parameters $\mathbf{w}$ of a module $A(\mathbf{w})$ remain in the *domain of legal values* $\mathcal{D}_A$, the module develops in a continuous way. Once the parameter values reach the boundary C_A of the domain $\mathcal{D}_A$, a production replaces module $A(\mathbf{w})$ by its descendants in a discrete event. The form of this production may depend on which segment C_{A_k} of the boundary of $\mathcal{D}_A$ has been crossed.

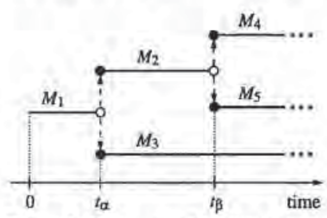

Figure 3: Fragment of the lineage tree of a hypothetical modular structure

For example, module M_2 in Figure 3 is created at time t_α as one of two descendants of the initial module M_1. It develops in the interval $[t_\alpha, t_\beta)$, and ceases to exist at time t_β, giving rise to two new modules M_4 and M_5. The instant t_β is the time at which parameters of M_2 reach the boundary of its domain of legal states $\mathcal{D}$. A hypothetical trajectory of module M_2 in its parameter space is depicted in Figure 4.

In order to formalize the above description, let us assume that the modeled structure consists of a sequence of modules (an extension to branching structures is straightforward if a proper definition of context is used [27, 28]). The state of the structure at time t is represented as a string:

$$\mu = A_1(\mathbf{w}_1)A_2(\mathbf{w}_2)\cdots A_n(\mathbf{w}_n).$$

The module $A_{i-1}(\mathbf{w}_{i-1})$ immediately preceding a given module $A_i(\mathbf{w}_i)$ in the string μ is called the *left neighbor* or *left context* of $A_i(\mathbf{w}_i)$, and the module $A_{i+1}(\mathbf{w}_{i+1})$ immediately following $A_i(\mathbf{w}_i)$ is called its *right neighbor* or *right context*. When it is inconvenient to list the indices, we use the symbols $<$, $>$, and/or subscripts l, r to specify the context of $A(\mathbf{w})$, as in the expression:

$$A_l(\mathbf{w}_l) < A(\mathbf{w}) > A_r(\mathbf{w}_r).$$

The continuous behavior of $A(\mathbf{w})$ is described by an *ordinary differential equation* that determines the rate of change $d\mathbf{w}/dt$ of parameters $\mathbf{w}$ as a function of the current value of these parameters and those of the module's neighbors:

$$\frac{d\mathbf{w}}{dt} = f_A(\mathbf{w}_l, \mathbf{w}, \mathbf{w}_r).$$

The above equation applies as long as the parameters $\mathbf{w}$ are in the domain $\mathcal{D}_A$ characteristic to the module type A. We assume that $\mathcal{D}_A$ is an open set, and specify its boundary C_A as the union of a finite number $m \geq 1$ of nonintersecting segments C_{A_k}, $k = 1, 2, \ldots, m$. The time t_β at which the trajectory of module $A(\mathbf{w})$ reaches a segment C_{A_k} of the boundary of $\mathcal{D}_A$ satisfies the expression:

$$\lim_{t \to t_\beta^-} \mathbf{w}(t) \in C_{A_k}.$$

The replacement of module $A(\mathbf{w})$ by its descendants at time t_β is described by a *production*:

$$p_{A_k} : A_l(\mathbf{w}_l) < A(\mathbf{w}) > A_r(\mathbf{w}_r) \longrightarrow$$
$$B_{k,1}(\mathbf{w}_{k,1})B_{k,2}(\mathbf{w}_{k,2})\cdots B_{k,m_k}(\mathbf{w}_{k,m_k}).$$

The module $A(\mathbf{w})$ is called the *strict predecessor* and the sequence of modules $B_{k,1}(\mathbf{w}_{k,1})B_{k,2}(\mathbf{w}_{k,2})\cdots B_{k,m_k}(\mathbf{w}_{k,m_k})$ is called the *successor* of this production. The index k emphasizes that different productions can be associated with individual segments C_{A_k} of the boundary C_A. The initial value of parameters assigned to a module $B_{k,j}(\mathbf{w}_{k,j})$ upon its creation is determined by a function $h_{A_{k,j}}$ which takes as its arguments the values of the parameters $\mathbf{w}_l$, $\mathbf{w}$, and $\mathbf{w}_r$ at the time immediately preceding production application:

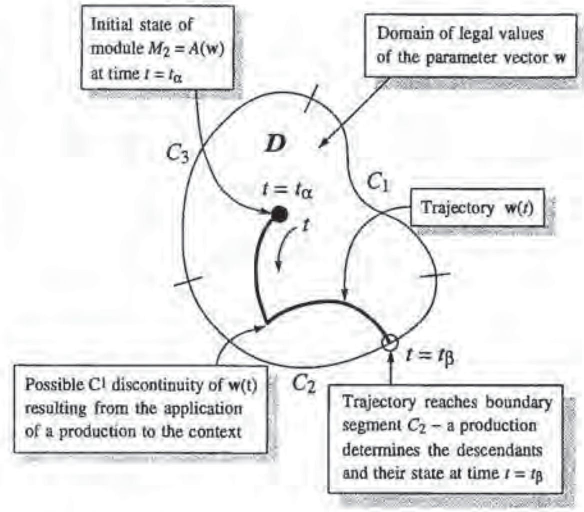

Figure 4: A hypothetical trajectory of module M_2 in its parameter space

$$\mathbf{w}_{k,j} = \lim_{t \to t_\beta^-} h_{A_{k,j}}(\mathbf{w}_l(t), \mathbf{w}(t), \mathbf{w}_r(t)).$$

The vector $\mathbf{w}_{k,j}$ must belong to the domain $\mathcal{D}_{B_{k,j}}$. (A stronger condition is needed to insure that the number of productions applied in any finite interval $[t, t + \Delta t]$ will be finite.)

In summary, a differential L-system is defined by the initial string of modules μ_0 and the specification of each module type under consideration. The specification of a module type A consists of four components:

$$< \mathcal{D}_A, C_A, f_A, P_A >,$$

where:

- the open set $\mathcal{D}_A$ is the domain of legal parameter values of modules of type A,
- the set $C_A = C_{A_1} \cup \ldots \cup C_{A_m}$ is the boundary of $\mathcal{D}_A$, consisting of nonintersecting segments $C_{A_1}, \ldots, C_{A_m}$,
- the function f_A specifies a system of differential equations that describe the continuous behavior of modules of type A in their domain of legal parameter values $\mathcal{D}_A$,
- the set of productions $P_A = \{p_{A_1}, \ldots, p_{A_m}\}$ captures the discrete behavior of modules of type A.

A production $p_{A_k} \in P_A$ is applied when the parameters of a module M of type A reach segment C_{A_k} of the boundary C_A. At this time module M disappears, and zero, one, or more descendant modules are created. The functions $h_{A_{k,j}}$ embedded in productions p_{A_k} determine the initial values of parameters in the successor modules.

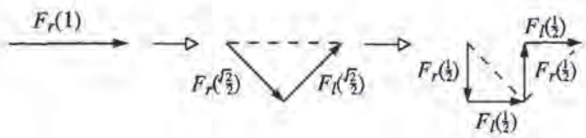

Figure 5: Initial steps in the construction of a dragon curve

4 EXAMPLES OF dL-SYSTEMS

We will illustrate the notion of a dL-system using two sample models suitable for animating the development of the *dragon curve* and the filamentous alga *Anabaena catenula*.

4.1 A dL-system model of the dragon curve

In the discrete case, consecutive iterations of the *dragon curve* (described, for example, in [27, Chapter 1]) can be obtained by the following parametric L-system:

$$\begin{aligned} \omega &: \; --F_r(1) \\ p_1 &: \; F_r(s) \rightarrow -F_r(s\tfrac{\sqrt{2}}{2}) + +F_l(s\tfrac{\sqrt{2}}{2})- \\ p_2 &: \; F_l(s) \rightarrow +F_r(s\tfrac{\sqrt{2}}{2}) - -F_l(s\tfrac{\sqrt{2}}{2})+ \end{aligned}$$

Assuming that symbols + and − represent turns of ±45°, this L-system encodes a Koch construction [18, Chapter 6] that repeatedly substitutes sides of an isosceles right-angled triangle for its hypotenuse (Figure 5). Subscripts l and r indicate that the triangle is formed respectively on the left or right side of the oriented predecessor segment. A corresponding dL-system that generates the dragon curve through the continuous progression of shapes indicated in Figure 6 is given below:

initial string: $--F_r(1,1)$
$F_r(x,s)$:
  if $x < s$ **solve** $\frac{dx}{dt} = \frac{s}{T}, \frac{ds}{dt} = 0$
  if $x = s$ **produce** $-F_r(0, s\frac{\sqrt{2}}{2}) + F_h(s,s) + F_l(0, s\frac{\sqrt{2}}{2})-$
$F_l(x,s)$:
  if $x < s$ **solve** $\frac{dx}{dt} = \frac{s}{T}, \frac{ds}{dt} = 0$
  if $x = s$ **produce** $+F_r(0, s\frac{\sqrt{2}}{2}) - F_h(s,s) - F_l(0, s\frac{\sqrt{2}}{2})+$
$F_h(x,s)$:
  if $x > 0$ **solve** $\frac{dx}{dt} = -\frac{s}{T}, \frac{ds}{dt} = 0$
  if $x = 0$ **produce** ε

The operation of this model starts with the replacement of the initial module $F_r(1,1)$ with the string:

$$-F_r(0, \frac{\sqrt{2}}{2}) + F_h(1,1) + F_l(0, \frac{\sqrt{2}}{2})-,$$

which has the same turtle interpretation: a line segment of unit length [1]. Next, the horizontal line segment represented by module F_h decreases in length with the speed $\frac{dx}{dt} = -\frac{1}{T}$, while the diagonal segments represented by modules F_r and F_l elongate with the speed $\frac{dx}{dt} = \frac{\sqrt{2}}{2}\frac{1}{T}$. The constant T determines the lifetime of the modules: after time T, the module F_h reaches zero length and is removed from the string (replaced by the empty string ε), while both modules F_r and F_l reach their maximum length of $\frac{\sqrt{2}}{2}$ and are replaced by their respective successors. These successors subsequently follow the same developmental pattern.

It is not accidental that the predecessor and the successor of the productions for $F_r(x,s)$ and $F_l(x,s)$ have identical geometric interpretations. Since productions are assumed to be applied instantaneously, any change of the model's geometry introduced by a production would appear as a discontinuity in the animation. In general, correctly specified productions satisfy *continuity criteria* [27, Chapter 6], which means that they conserve physical entities such as shape, mass, and velocity of modules.

4.2 A dL-system model of *Anabaena catenula*

The continuously developing dragon curve has been captured by a context-free dL-system, in which all productions and equations depend only on the strict predecessor module. A simple example of a context-sensitive model inspired by the development of the blue-green alga *Anabaena catenula* [3, 20, 27] is given below.

Anabaena forms a nonbranching filament consisting of two classes of cells: *vegetative cells* and *heterocysts*. A vegetative cell usually divides into two descendant vegetative cells. However, in some cases a vegetative cell differentiates into a heterocyst. The spacing between heterocysts is relatively constant, in spite of the continuing growth of the filament. Mathematical models explain this phenomenon using a biologically motivated hypothesis that the distribution of heterocysts is regulated by nitrogen compounds produced by the heterocysts, diffusing from cell to cell along the filament, and decaying in the vegetative cells. If the compound concentration in a vegetative cell falls below a specific level, this cell differentiates into a heterocyst (additional factors are captured by more sophisticated models). A model operating in continuous time according to this description can be captured by the following dL-system:

initial string: $F_h(x_{max}, c_{max})F_v(x_{max}, c_{max})F_h(x_{max}, c_{max})$
$F(x_l, c_l) < F_v(x,c) > F(x_r, c_r)$:
  if $x < x_{max}$ & $c > c_{min}$
    solve $\frac{dx}{dt} = rx, \frac{dc}{dt} = D \cdot (c_l + c_r - 2c) - \mu c$
  if $x = x_{max}$ & $c > c_{min}$
    produce $F_v(kx_{max}, c)F_v((1-k)x_{max}, c)$
  if $c = c_{min}$
    produce $F_h(x,c)$
$F_h(x,c)$:
    solve $\frac{dx}{dt} = r_x(x_{max} - x), \frac{dc}{dt} = r_c(c_{max} - c)$

Vegetative cells F_v and heterocysts F_h are characterized by their length x and concentration of nitrogen compounds c. The differential equations for the vegetative cell F_v indicate that while the cell length x is below the maximum value x_{max} and the compound concentration c is above the threshold c_{min}, the cell elongates exponentially according to the equation $\frac{dx}{dt} = rx$, and the compound concentration changes according to the equation:

$$\frac{dc}{dt} = D \cdot (c_l + c_r - 2c) - \mu c.$$

The first term in this equation describes diffusion of the compounds through the cell walls. Following *Fick's law* [5, page 404], the

[1] The turtle interprets the first parameter as the segment length, and ignores the second parameter.

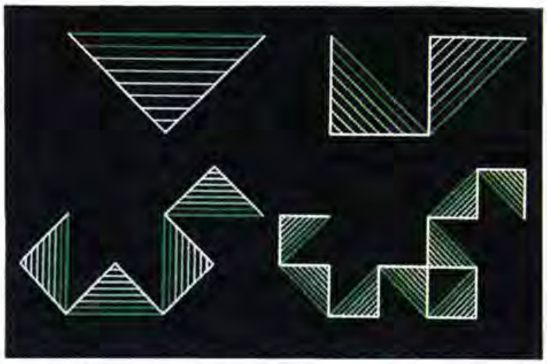

Figure 6: Development of the dragon curve simulated using a dL-system, recorded in time intervals $\Delta t = \frac{1}{8}T$. Top left: Superimposed stages $0-8$, top right: stages $8-16$, bottom row: stages $16-24$ and $24-32$.

Figure 7: Diagrammatic representation of the development of *Anabaena catenula*, simulated using a dL-system with the constants set to the following values: $x_{max} = 1$, $c_{max} = 255$, $c_{min} = 5$, $D = \mu = 0.03$, $r = 1.01$, $k = 0.37$, $r_x = 0.1$, $r_c = 0.15$. The development was recorded from $t_{min} = 200$ to $t_{max} = 575$ at the intervals $\Delta t = 1$. Developmental stages are shown as horizontal lines with the colors indicating the concentration c of nitrogen compounds. Dark brown represents c_{min}; white represents c_{max}.

rate of diffusion is proportional to the differences of compound concentrations, $c_r - c$ and $c_l - c$, between the neighbor cells and the cell under consideration. The term μc describes exponential decay of the compounds in the cell.

In addition to the differential equations, two productions describe the behavior of a vegetative cell. If the cell reaches maximum length x_{max} while the concentration c is still above the threshold c_{min}, the cell divides into two vegetative cells of length kx_{max} and $(1-k)x_{max}$, with the compound concentration c inherited from their parent cell. Otherwise, if the concentration c drops down to the threshold c_{min}, the cell differentiates into a heterocyst. Both productions satisfy the continuity criteria by conserving total cell length and concentration of nitrogen compounds.

The last line of the model specifies the behavior of the heterocysts. Their length and compound concentration converge exponentially to the limit values of x_{max} and c_{max}. The heterocysts do not undergo any further transformations.

Simulation results obtained using the above model are shown in Figure 7. The cells in the filament are represented as horizontal line segments with the colors indicating the concentration of nitrogen compounds. Consecutive developmental stages are drawn one under another. An approximately equal spacing between the heterocysts (shown in white) is maintained for any horizontal section, as postulated during model formulation.

Note that for incorrectly chosen constants in the model, the spacing between heterocysts may be distorted; for example, groups of adjacent vegetative cells may almost simultaneously differentiate into heterocysts.

5 EVALUATION OF dL-SYSTEMS

Although Figures 6 and 7 were obtained using dL-systems, we have not yet discussed the techniques needed to *evaluate* them. This term denotes the calculation of the sequence of strings $\mu(0) = \mu_0$, $\mu(\Delta t) = \mu_1, \ldots, \mu(n\Delta t) = \mu_n$ representing the states of the modeled structure at the desired intervals Δt. We address the problem of dL-system evaluation in the framework of the combined discrete/continuous paradigm for system simulation introduced by Fahrland [6] and presented in a tutorial manner by Kreutzer [15].

According to this paradigm, the evaluation can be viewed as a *dynamic process* governed by a *scheduler*: a part of the simulation program that monitors the state of the model, advances time, and dispatches the activities to be performed. In the absence of discrete events (productions), the scheduler repeatedly advances time by the *time slice* Δt. During each slice, the differential equations associated with the modules are integrated numerically (using an integration technique appropriate for the equations in hand), thus advancing the state of the structure from $\mu(t)$ to $\mu(t+\Delta t)$. If the scheduler detects that a discrete event should occur (i.e., a production should be applied) at time t' within the interval $[t, t+\Delta t)$, this interval is divided into two subintervals $[t, t')$ and $[t', t+\Delta t)$. The differential equations are integrated in the interval $[t, t')$ and yield parameter values for the production application at time t'. The production determines the initial values for the differential equations associated with the newly created modules; these equations are integrated in the remaining interval $[t', t+\Delta t)$. Each of the intervals $[t, t')$ and $[t', t+\Delta t)$ is subdivided further if more discrete events occur during $[t, t+\Delta t)$.

Plant structures generated using dL-systems may consist of large numbers (thousands) of modules. If many modules are replaced at different times t' during the interval $[t, t+\Delta t)$, the global advancement of time may require an excessive subdivision of this interval, leading to a slow evaluation of the model. This problem can be solved by detecting and processing events the interval $[t, t+\Delta t)$ individually for each module. The increase of simulation speed is obtained at the expense of accuracy, since the state of the context of a module replaced at time $t' \in (t, t+\Delta t)$ must be approximated, for example, by its state at time t. No accuracy is lost in the context-free case.

In the above description we assumed that the scheduler is capable of detecting each instant t' at which a discrete event occurs. If the differential equations are sufficiently simple, we can solve them analytically and determine time t' explicitly. In general, we need numerical techniques for special event location in piecewise-continuous ordinary differential equations, as described by Shampine *et. al.* [29], and Barzel [2, Appendix C].

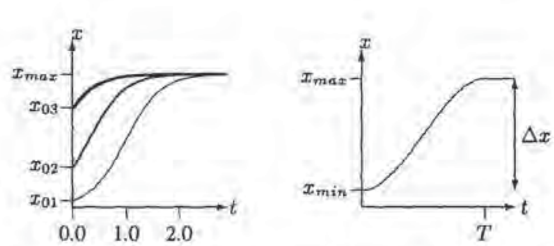

Figure 8: Examples of sigmoidal growth functions. a) A family of logistic functions plotted using $r = 3.0$ for different initial values x_0. b) A cubic function $G_{\Delta x, T}$.

6 GROWTH FUNCTIONS

Growth functions describe continuous processes such as the expansion of individual cells, elongation of internodes, and gradual increase of branching angles over time. For example, the differential equations included in the dL-system for the dragon curve (Section 4.1) describe linear elongation of segments F_r and F_l, and linear decrease in length of segments F_h. The dL-system model of *Anabaena* (Section 4.2) assumes exponential elongation of cells.

In higher plants, the growth functions are often of *sigmoidal* (S-shaped) type, which means that they initially increase in value slowly, then accelerate, and eventually level off at or near the maximum value. A popular example of a sigmoidal function is Velhurst's *logistic* function (c.f. [5, page 212]), defined by the equation:

$$\frac{dx}{dt} = r\left(1 - \frac{x}{x_{max}}\right)x$$

with a properly chosen initial value x_0 (Figure 8a). Specifically, x_0 must be greater than zero, which means that neither the initial length nor the initial growth rate of a module described by the logistic function will be equal to zero. In order to obtain a continuous progression of forms, it is often convenient to use a growth function that has zero growth rates at both ends of an interval T within which its value increases from x_{min} (possibly zero) to x_{max}. These requirements can be satisfied, for example, by a *cubic* function of time. Using the Hermite form of curve specification [8, page 484], we obtain:

$$x(t) = -2\frac{\Delta x}{T^3}t^3 + 3\frac{\Delta x}{T^2}t^2 + x_{min},$$

where $\Delta x = x_{max} - x_{min}$ and $t \in [0, T]$. The equivalent differential equation is:

$$\frac{dx}{dt} = -6\frac{\Delta x}{T^3}t^2 + 6\frac{\Delta x}{T^2}t = 6\frac{\Delta x}{T^2}\left(1 - \frac{t}{T}\right)t$$

with the initial condition $x_0 = x_{min}$. In order to extend this curve to infinity (Figure 8b), we define:

$$\frac{dx}{dt} = G_{\Delta x, T}(t) = \begin{cases} 6\frac{\Delta x}{T^2}\left(1 - \frac{t}{T}\right)t & \text{for } t \in [0, T] \\ 0 & \text{for } t \in (T, +\infty). \end{cases}$$

Although the explicit dependence of the function G on time is questionable from the biological point of view (a plant module does not have a means for measuring time directly), parametric cubic functions constitute a well understood computer graphics tool [8, Chapter 11.2] and can be conveniently used to approximate the observed changes of parameter values over time.

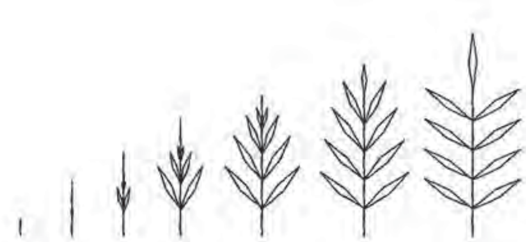

Figure 9: Development of a compound leaf simulated using a dL-system. Parameter values are: $n_0 = 4$, $x_0 = 1.0$, $x_{th} = 2.0$, $k = 0.5$, $r_a = 2.0$, $x_{amax} = 3.0$, $r_i = 1.0$, $x_{imax} = 3.0$, $s_0 = 0.05$, $r_s = 2.0$, $s_{max} = 6.0$, $\alpha_0 = 2.0$, $r_\alpha = 1.0$, $\alpha_{max} = 60.0$, and $\Delta t = 0.01$. The stages shown represent frames 50, 215, 300, 400, 500, 600, and 900 of an animated sequence.

7 MODELING OF HIGHER PLANTS

In this section we present sample applications of dL-systems to the animation of the development of higher plants.

7.1 Pinnate Leaf

A pinnate leaf provides a simple example of a *monopodial* branching structure. *Monopodial* branching occurs when the apex of the main axis produces a succession of *nodes* bearing *organs* — leaves or flowers — which are separated by *internodes*. In the case of pinnate leaves with the leaflets occurring in pairs (termed *opposite* arrangement), the essence of this process can be captured by the L-system production [27, page 71]:

$$F_a \longrightarrow F_i[+@L][-@L]F_a,$$

where F_a denotes the apex, F_i — an internode, and $@L$ — a leaflet. The dL-system model given below extends this L-system with growth functions that control the expansion of all components and gradually increase branching angles over time.

initial string: $F_a(x_0, n_0)$
$F_a(x, n)$:
  if $x < x_{th}$
    solve $\frac{dx}{dt} = r_a\left(1 - \frac{x}{x_{amax}}\right)x$, $\frac{dn}{dt} = 0$
  if $x = x_{th}$ & $n > 0$
    produce $F_i(kx)[+(\alpha_0)@L(s_0)][-(\alpha_0)@L(s_0)]$
      $F_a((1-k)x, n-1)$
  if $x = x_{th}$ & $n = 0$
    produce $F_i(x)@L(s_0)$
$F_i(x)$: **solve** $\frac{dx}{dt} = r_i\left(1 - \frac{x}{x_{imax}}\right)x$
$L(s)$: **solve** $\frac{ds}{dt} = r_s\left(1 - \frac{s}{s_{max}}\right)s$
$\pm(\alpha)$: **solve** $\frac{d\alpha}{dt} = r_\alpha\left(1 - \frac{\alpha}{\alpha_{max}}\right)\alpha$

The apex F_a has two parameters x and n which indicate its current length and the remaining number of internodes to be produced. The apex elongates according to the logistic function with parameters r (controlling growth rate) and x_{amax} (controlling the asymptotic apex length). Upon reaching the threshold length x_{th}, the apex produces a pair of leaflets $@L$ and subdivides into an internode F_i of length kx and a shorter apex of length $(1-k)x$. Once the predefined number n_0 of leaf pairs have been created, the apex

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Figure 10: Development of the herbaceous plant *Campanula rapunculoides*. The snapshots show every 25^{th} frame of a computer animation, starting with frame 175.

transforms itself into an internode and produces the terminal leaflet. The length of internodes, the size of leaflets, and the magnitude of the branching angles increase according to the logistic functions. Snapshots of the leaf development simulated by the above model are shown in Figure 9.

7.2 *Campanula rapunculoides*

The inflorescence of *Campanula rapunculoides* (creeping bellflower) has a monopodial branching structure similar to that of a pinnate leaf; consequently, it is modeled by a similar dL-system:

initial string: $F_a(x_0, n_0)$

$F_a(x,n)$:
- **if** $x < x_{th}$
  - **solve** $\frac{dx}{dt} = v$, $\frac{dn}{dt} = 0$
- **if** $x = x_{th}$ & $n > 0$
  - **produce** $F_i(kx)[+(\alpha_0)@K]F_a((1-k)x, n-1)$
- **if** $x = x_{th}$ & $n = 0$
  - **produce** $F_i(x)@K$

$F_i(x)$: **solve** $\frac{dx}{dt} = G_{\Delta x, T_1}(t)$

$+(\alpha)$: **solve** $\frac{d\alpha}{dt} = G_{\Delta\alpha, T_2}(t)$

The apex is assumed to grow at a constant speed. Cubic growth functions describe the elongation of internodes and the gradual increase of branching angles. The combination of the linear growth of the apex with the cubic growth of the internodes results in first-order continuity of the entire plant height (except when apex F_a is transformed into internode F_i and terminal flower $@K$).

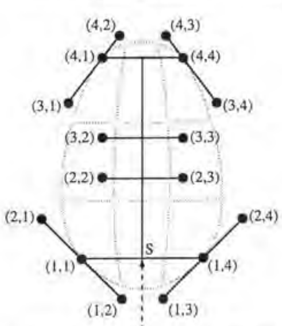

Figure 11: A Bézier patch defined by a branching structure

Figure 10 presents a sequence of snapshots from an animation of *Campanula*'s development. It was obtained using the above dL-system augmented with rules that govern the development of flowers $@K$ from a bud to an open flower to a fruit. The petals and sepals have been modeled as Bézier patches, specified by control points placed at the ends of simple branching structures (Figure 11). Each structure is

Figure 12: Development of a single flower of *Campanula rapunculoides*

attached to the remainder of the model at point S. The lengths of the line segments and the magnitudes of the branching angles have been controlled by cubic growth functions, yielding the developmental sequence shown in Figure 12. When the flower transforms into a fruit, productions instantaneously remove the petals from the model (it is assumed that the time over which a petal falls off is negligible compared to the time slice used for the animation of development). Manipulation of Bézier patches using L-systems has been described in detail by Hanan [13].

7.3 *Lychnis coronaria*

The inflorescence of *Lychnis coronaria* (rose campion) is an example of a sympodial branching structure, characterized by large branches that carry the main thrust of development. As presented in [27, page 82] and [28], the apex of the main axis turns into a flower shortly after the initiation of a pair of lateral branches. Their apices turn into flowers as well, and second-order branches take over. The lateral branches originating at a common node develop at the same rate, but the development of one side is delayed with respect to the other. This process repeats recursively, as indicated by the following L-system:

$$\begin{array}{lll} \omega : & A_7 & \\ p_1 : & A_7 \longrightarrow F[A_0][A_4]F@K & \\ p_2 : & A_i \longrightarrow A_{i+1} & 0 \le i < 7 \end{array}$$

Production p_1 shows that, at their creation time, the lateral apices have different states A_0 and A_4. Consequently, the first apex requires eight derivation steps to produce flower $@K$ and initiate a new pair of branches, while the second requires only four steps.

A corresponding dL-system using cubic growth functions to describe the elongation of internodes F is given below:

initial string: $A(\tau_{max})$

$A(\tau)$:
- **if** $\tau < \tau_{max}$ **solve** $\frac{d\tau}{dt} = 1$
- **if** $\tau = \tau_{max}$ **produce** $F(0)[A(0)][A\left(\frac{\tau_{max}}{2}\right)]F(0)@K$

$F(x)$: **solve** $\frac{dx}{dt} = G_{\Delta x, T}(t)$

For simplicity, we have omitted leaves and symbols controlling the relative orientation of branches in space. The operation of the model

Figure 13: Development of *Lychnis coronaria*. The snapshots show every 25^{th} frame of a computer animation, starting with frame 150.

is governed by apices A characterized by their age τ and assumed to have negligible size. Upon reaching the maximum age τ_{max}, an apex splits into two internodes F, creates two lateral apices A with different initial age values 0 and $\frac{\tau_{max}}{2}$, and initiates flower $@K$. In order to satisfy continuity criteria, the initial length of internodes is assumed to be zero.

Figure 13 shows selected snapshots from an animation of the development of *Lychnis* obtained using an extension of this dL-system. As in *Campanula*, the individual flowers have been modeled using Bézier patches controlled by the dL-system.

7.4 *Hieracium umbellatum*

The compound leaf and the inflorescences of *Campanula* and *Lychnis* have been captured by context-free dL-systems, assuming no flow of information between coexisting modules. Janssen and Lindenmayer [14] (see also [27, Chapter 3] and [28]) showed that context-free models are too weak to capture the whole spectrum of developmental sequences in plants. For example, the *basipetal* flowering sequence observed in many compound inflorescences requires the use of one or more signals that propagate through the developing structure and control the opening of buds. Such a sequence is characterized by the first flower opening at the top of the main axis and the flowering zone progressing downward towards the base of the plant.

Figure 14: A model of *Hieracium umbellatum*.

Figure 14 shows a synthetic image of *Hieracium umbellatum*, a sample composite plant with a basipetal flowering sequence. Following *model I* postulated by Janssen and Lindenmayer, we assume that the opening of buds is controlled by a *hormone* generated at some point of time near the base of the plant and transported towards the apices. The hormone propagates faster in the main axis than in the lateral branches. As a result, it first reaches the bud of the main axis, then those of the lateral branches in the basipetal sequence. The growth of the main axis and of the lateral branches stops when the hormone attains their respective terminal buds. In addition, the hormone penetrating

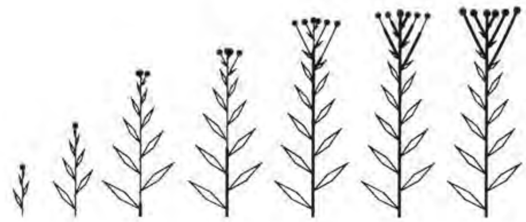

Figure 15: Development of *Hieracium umbellatum*. The stages shown represent frames 170, 265, 360, 400, 470, 496, and 520 of an animated sequence.

a node stops the development of a leaf originating at this node. Snapshots from a diagrammatic animated developmental sequence illustrating this process are shown in Figure 15.

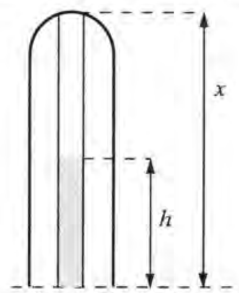

Figure 16: A conceptual model of the apex.

The complete listing of the dL-system capturing the development of *Hieracium* is too long to be included in this paper, but a specification of the activities of the main apex provides a good illustration of the context-sensitive control mechanism involved. We conceptualize this apex as a growing and periodically dividing tube of length x, which may be penetrated by the hormone to a height $h \leq x$ (Figure 16). The apex can assume three states: F_{a0} (not yet reached by the hormone), F_{a1} (being penetrated by the hormone), and F_{a2} (completely filled with the hormone). The apical behavior is captured by the following rules:

$F_l(x_l, h_l) < F_{a0}(x)$:
  if $x_l > h_l \;\&\; x < x_{th}$
    solve $\frac{dx}{dt} = G(x)$
  if $x = x_{th}$
    produce $F_{i0}(kx)[F_{a0}(0)]F_{a0}((1-k)x)$
  if $x_l = h_l \;\&\; x < x_{th}$
    produce $F_{a1}(x, 0)$
$F_{a1}(x, h)$:
  if $x > h \;\&\; x < x_{th}$
    solve $\frac{dx}{dt} = G(x),\;\; \frac{dh}{dt} = v$
  if $kx > h \;\&\; x = x_{th}$
    produce $F_{i1}(kx, h)[F_{a0}(0)]F_{a0}((1-k)x)$
  if $x > h \geq kx \;\&\; x = x_{th}$
    produce $F_{i2}(kx, kx)F_{a1}((1-k)x, h - kx)$
  if $x = h$
    produce $F_{a2}(x, x)$

The first three rules model the apex without the hormone. If the preceding internode F_l is not yet completely penetrated by the hormone ($x_l > h_l$) and the length x of the apex is below the threshold value x_{th}, the apex elongates according to the growth function $G(x)$. Upon reaching the threshold length ($x = x_{th}$), the apex F_{a0} subdivides, producing an internode F_{i0} and a lateral apex F_{a0}. Finally, once the hormone penetrates the entire internode F_l (as indicated by the condition $x_l = h_l$), it flows into the apex, which then changes its state to F_{a1}.

Figure 17: Development of a single flower head of *Hieracium umbellatum*

The continuous rule for F_{a1} describes the growth of the apex with rate $G(x)$ and the propagation of the hormone with constant speed v. The next two productions capture the alternate cases of the apex subdivision, with the hormone level h below or above the level kx at which the new internode splits from the apex. The last production is applied when the hormone reaches the tip of the apex, and changes its state to the flowering state F_{a2}.

The complete model of *Hieracium umbellatum* contains additional rules that describe the elongation of internodes, the propagation of the hormone within and between the internodes, and the development of flower heads. The heads undergo the sequence of transformations illustrated in Figure 17. The bracts (green parts of the flower head) have been represented using Bézier patches controlled by the dL-system, while the petals have been formed as extending chains of filled rectangles, with the angles between consecutive rectangles controlled by cubic growth functions. This technique allowed us to represent each petal with a relatively modest number of polygons (10).

8 CONCLUSIONS

We have introduced differential L-systems as a combined discrete/continuous model suitable for computer simulation and animation of plant development. Continuous aspects of module behavior are described by ordinary differential equations, and discontinuous qualitative changes are captured by productions. The link between L-systems and dL-systems makes it possible to use existing discrete developmental models as a starting point for constructing dL-systems suitable for animation.

Differential L-systems have a wide spectrum of prospective applications, ranging from modest projects, such as the diagrammatic animation of developmental mechanisms employed by plants, to ambitious ones, such as the realistic animation of the growth of extinct plants. On the conceptual level, dL-systems expand piecewise-continuous differential equations with a formal specification of discrete changes to system configuration. The resulting formalism makes it possible to model developing branching structures with a theoretically unlimited number of modules. From a different perspective, dL-systems can be considered as the continuous-time extension of parametric L-systems.

The following problems still require solutions:

- **Combined differential-algebraic specification of continuous processes.** In some cases it is convenient to describe continuous aspects of model behavior using explicit functions of time instead of differential equations. For example, the expression of the cubic growth function using the differential equation presented in Section 6 is somewhat artificial. In order to accommodate explicit function specifications, the definition of dL-systems should be extended to comprehend differential-algebraic equations.
- **Incorporation of stochastic rules.** Differential L-systems have been formulated in deterministic terms. Stochastic rules should be incorporated to capture the specimen-to-specimen variations in modeled plants, as has been done for L-systems.
- **Development of the simulation software.** The simulations discussed in this paper were carried out using a programming language based on parametric L-systems [13, 26]. In this environment, the user must explicitly specify the formulae for numerically solving the differential equations included in the models (the forward Euler method was used in all cases). From the user's perspective, it would be preferable to incorporate a differential equation solver into the simulator, and specify the models directly in terms of dL-systems.
- **Improved realism of dL-system models.** We have not addressed many practical problems related to the construction of realistic models, such as the avoidance of intersections between modules, the improved modeling of growing plant organs (petals, leaves, and fruits), and the simulation of wilting.

The simulation and visualization of natural phenomena has the intriguing charm of blurring the line dividing the synthesis of images from the re-creation of nature. The animation of plant development adds a new phenomenon to this (un)real world.

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Modeling Soil: Realtime Dynamic Models for Soil Slippage and Manipulation

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ABSTRACT

A physically based model of an object is a mathematical representation of its behavior, which incorporates principles of Newtonian physics. Dynamic soil models are required in animations and realtime interactive simulations in which changes of natural terrain are involved. Analytic methods, based on soil properties and Newtonian physics, are presented in the paper to model soil slippage and soil manipulations. These methods can be used to calculate the evolution of a given soil configuration under the constraint of volume conservation and to simulate excavating activities such as digging, cutting, piling, carrying or dumping soil. Numerical algorithms with linear time and space complexities are also developed to meet the requirement of realtime computer simulation.

CR Categories: I.3.7 [Computer Graphics]: Graphics and Realism; I.6.3 [Simulation and Modeling]: applications.
Additional Keywords: physically based modeling, real-time simulation, soil dynamics, slippage, soil manipulation.

1. INTRODUCTION

Physically-based modeling is a growing area of computer graphics research. A good deal of work has been done toward physically based models of objects such as rigid and nonrigid bodies, hydraulic surfaces or natural terrain. However, soil models that are both physically realistic and computationally efficient in realtime simulations have not been developed. Recently, substantial interest in dynamic soil models has been expressed by some developers of realtime simulations of Dynamic Terrain systems. Such systems provide the capability, within a realtime graphical simulation, of reconstructing landscape architecture or rearranging the terrain surface. These systems essentially involve allowing the simulation's user to conduct excavating activities in the terrain database at any freely chosen location. These activities may include digging ditches, piling up dirt, cutting the soil mass from the ground, carrying it for a distance, and dumping it at another location. To these deformations, the soil mass must behave in realistic manners under external stimuli.

Moshell and Li developed a visually plausible kinematic soil model [10]. In their work, a bulldozer blade serves as a local force function used to change the heights of the terrain. Excess terrain volume which is "scaped off" by the moving blade is added to the moving berm in front of the blade. The berm is then smoothed by a bidirectional Cardinal spline algorithm. The demonstration of the model appears realistic and runs in realtime. The simulation, however, is kinematic. No forces are computed. The soil does not slump when the bulldozer leaves. The volume of given soil is not conserved.

Burg and Moshell focussed on the problem of piling up soil such that the soil spills down from the mounds in a realistic-looking way [3]. In their approach, the terrain is modeled by a 2-d grid of altitude posts. Constraint equations are defined to describe relationships among altitude posts and their neighbors. An iterative relaxation algorithm, suggested in [11], is used to simulate the falling soil. The constraints enforce an averaging or "smoothing" of each altitude post with its neighbors. The algorithm is volume-preserving under certain conditions. The model is purely kinematic. The physical properties of different types of soil are not modeled.

Our research work is focused on dynamic models of soil slippage and soil manipulations. For the slippage model, we determine if a given soil configuration is in static equilibrium, calculate forces which drive a portion of the soil to slide if the configuration is not stable, and meanwhile preserve the volume conservation. For the soil manipulation models, we investigate interactions between soil and excavating machines, implement a bulldozer model and a scooploader model. These models are based on analytic methods and Newtonian physics. The computational times of the corresponding algorithms are fast enough to meet the requirement of realtime graphical simulations. For clarity, this paper mainly focuses on the 2-d case. Extensions to 3-d have been completed and are briefly discussed.

2. PRELIMINARIES

The discussion of soil models needs some understanding of soil properties. In this section, we introduce some concepts which are borrowed directly from civil engineering. Interested readers are referred to [2], [4], [5] and [7] for more details.

The *shear strength* of the soil is the resistance per unit area to deformation by continuous shear displacement of soil particles along surfaces of rupture. It may be attributed to three basic components: 1) frictional resistance to sliding among soil particles; 2) cohesion and adhesion among soil particles; and 3) interlocking of solid particles to resist deformation. (Cohesion is molecular attraction among like particles. Adhesion is a molecular attraction among unlike particles.)

The *shear stress*, on the other hand, is the force per unit area experienced by a slope, which pushes the mass to move along the failure plane. The combined effects of gravity and water are the primary influences on the shear stress. It may also be influenced by some natural phenomena such as chemical actions, earthquakes, or wind.

The shear *strength force* and *stress force*, denoted by s and τ respectively, are defined as the shear strength and stress multiplied by the total area. The measure of s and τ can be determined from the *Mohr-Coulomb theory* indicated in [5]:

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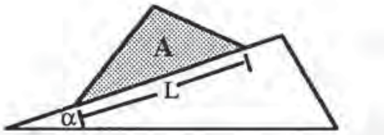

Fig. 1: The Failure Plane

(2.1) $s = c\,L + W \cos(\alpha) \tan(\phi)$

(2.2) $\tau = W \sin(\alpha)$

where L is the length of the failure plane, α is the degree of natural slope, and $W=\gamma A$ is the weight of soil above the failure plane (see Fig. 1). c, ϕ and γ describe properties of the soil, where c indicates the cohesion, ϕ is the angle of internal friction (i.e. it is a measure of the friction among soil particles) and γ is the unit weight. Some typical parameters and their units are listed in the table below [1]:

SOIL TYPE	c (t/m)	ϕ (degree)	γ (t/m^2)
dry sand	0	26-33	1.9-2.0
Sandy loam	0-2.0	14-26	1.8-2.0
Loam	0.5-5.0	10-28	1.8-2.1

Soil is a very complex material. It may be influenced by changes in the moisture content, pore pressures, structural disturbance, fluctuation in the ground water table, underground water movements, stress history, time, chemical action or environmental conditions. Predicting the changes of complex configurations is either intractable or highly costly. However, for many interactive applications, speed and realistic appearance are more important than accuracy. Hence in this paper, we assume that only homogeneous and isotropic soil will be processed. Conditions such as seepage, pore pressure, existence of tension cracks and deformation resulting from permanent atomic dislocation will not be considered.

3. STATIC EQUILIBRIUM AND RESTORING FORCE

In this section, we develop methods to determine whether or not a given configuration is stable, calculate the critical angle above which sliding occurs, and quantify the force which pushes the soil mass moving along the failure plane.

3.1 STABILITY

The stability of a given soil configuration is determined by the *factor of safety*, denoted by F, of a potential failure surface. From the Mohr-Coulomb theory, F is defined as a ratio between the strength force and the stress force [5]:

(3.1) $$F = \frac{s}{\tau} = \frac{c\,L + W\cos(\alpha)\tan(\phi)}{W\sin(\alpha)}$$

When F is greater than 1, the configuration is said to be in a state of equilibrium. Otherwise, failure is imminent. To analyze the factor of safety, we divide the given soil mass into n slices with equal width Δx:

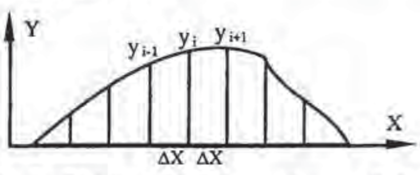

Fig. 2: Dividing the given mass into small slices

The calculation of the factor of safety of each slice can be done individually. The following free body diagram shows forces applied on slice i:

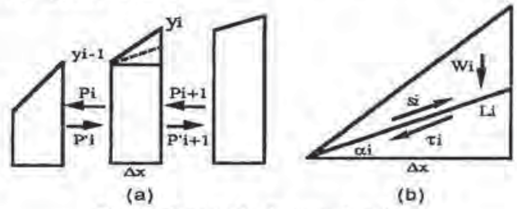

Fig. 3: Free body diagram for slice i

In (a), the P's are forces exerted between slices. They are pairwise equal and in opposite directions and thus can be cancelled. At any time t, therefore, sliding can only happen in the top triangle area of a slice. (b) shows forces acting on this area, where strength and stress forces are given by (2.1) and (2.2) with L, W and α replaced by L_i, W_i and α_i respectively.

To determine if there exists a failure angle α_i (so that the soil mass above it will slide) and calculate the net force exerted on the failure plane if α_i does exist, we start from (3.1). Note that L_i and W_i can be expressed in terms of α_i. Replacing L_i and W_i in (3.1) with functions of α_i, we obtain

(3.2) $$F(\alpha_i) = \frac{2c+\gamma\tan(\phi)[h\cos(\alpha_i)-\Delta x\sin(\alpha_i)]\cos(\alpha_i)}{\gamma(h\cos(\alpha_i)-\Delta x\sin(\alpha_i))\sin(\alpha_i)}$$

where $h=y_i-y_{i-1}$ is the height of the triangle in Fig. 3-(b). For any angle $\alpha_i>\tan^{-1}(h/\Delta x)$, function $F(\alpha_i)$ makes no physical sense. In the range of $[0, \tan^{-1}(h/\Delta x)]$, $F(\alpha_i)$ reaches its minimum when the first derivative of $F(\alpha_i)$, with respect to α_i, is equal to 0. That is

(3.3) $$\frac{dF}{d\alpha} = \frac{1}{\tau^2}\,[A\cos(2\alpha_i) + B\sin(2\alpha_i) + C] = 0$$

where

$$A = \frac{\gamma^2}{2}\tan(\phi)(\Delta x^2-h^2)-2\gamma ch,$$

$$B = \gamma^2 h\Delta x\tan(\phi)+2\gamma c\Delta x, \text{ and}$$

$$C = -\frac{\gamma^2}{2}\tan(\phi)(\Delta x^2+h^2).$$

Solving (3.3) gives us four angles (see [9]). We can choose the one which satisfies $0\le\alpha_i\le\tan^{-1}(h/\Delta x)$ in (3.2) to calculate the factor of safety F. The given configuration is statically stable if F>1. Otherwise sliding is inevitable.

3.2 CRITICAL SLOPE ANGLE

Suppose that we have F<1 for a given configuration. In the range of $[0, \tan^{-1}(h/\Delta x)]$ there are at most two angles, say β_1 and β_2, such that $F(\beta_1)=F(\beta_2)=1$. The angle $\beta_0=\min(\beta_1, \beta_2)$ is said to be the *critical-slope angle* of the configuration. Above this angle impending slip occurs. β_1 and β_2 can be obtained by solving the equation (3.4) for α:

(3.4) $$F(\alpha) = \frac{2c+\gamma\tan(\phi)[h\cos(\alpha)-\Delta x\sin(\alpha)]\cos(\alpha)}{\gamma[h\cos(\alpha)-\Delta x\sin(\alpha)]\sin(\alpha)} = 1$$

where all symbols are as explained earlier. The solution to (3.4) is derived in [9].

3.3 RESTORING FORCE

Let a configuration be given in Fig.4-(a) with β_0 as the critical-slope angle. The force that pushes the mass in the triangle along the edge gh_0 can be computed as follows. First the line segment h_0h_n is divided into n small segments with equal length Δh. Fig 4-(b) shows the free body diagram of the i-th dovetail indicated by the shaded area in (a).

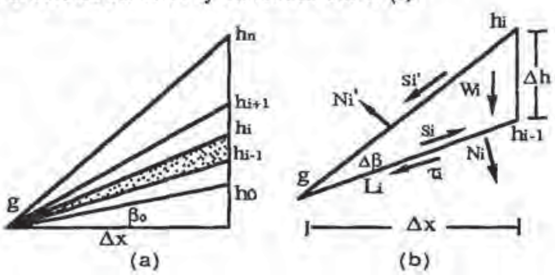

Fig. 4: Analyzing the restoring force

Let's analyze forces exerted on the dovetail. The weight W_i can be decomposed into two forces, namely N_i and τ_i, which are normal and parallel to the edge L_i respectively. s_i is the strength force resisting the sliding motion, s_i' the opponent force generated by strength force s_{i+1}, and N_i' the force supporting the dovetail above it. The net force f_i applied on dovetail-i is therefore given by a vectorial summation:

(3.5) $$f_i = N_i + \tau_i + s_i + s_i' + N_i'$$

The total net force f acting on the whole triangle area is the summation of f_i's, $1 \le i \le n$, i.e.

(3.6) $$f = \sum_{i=1}^{n}(N_i+\tau_i+s_i+s_i'+N_i') = \sum_{i=2}^{n}\tau_i$$

since $\tau_1 = s_1$ (due to $F(\beta_0) = 1$), $N_n' = 0$, $s_n' = 0$, $N_i' = N_{i+1}$ and $s_i' = -s_{i+1}$ for $1 \le i \le n-1$. Based on (3.6) and Fig.4, [9] gives a derivation of (3.7) by letting Δh tend to zero.

(3.7) $$f = \frac{\gamma\Delta x^2}{4} \mathrm{Ln}\left(\frac{h_n^2+\Delta x^2}{h_0^2+\Delta x^2}\right)\cos(\beta_0) + \frac{\gamma\Delta x}{2}(h_n-h_0-\Delta x(\beta_n-\beta_0))\sin(\beta_0)$$

where $\beta_n = \tan^{-1}(h_n/\Delta x)$ and $\beta_0 = \tan^{-1}(h_0/\Delta x)$. (3.7) can be used to quantify the total force on the top triangle area of each slice.

4. VOLUME CONSERVATION

The approach used in this section is strongly related to [8]. Recall that, in the previous discussion, a given configuration is divided into n slices. The i-th slice, $1 \le i \le n$, can be conveniently thought of as a container holding an amount of soil whose quantity is given by $(y_i+y_{i-1})\Delta x/2$.

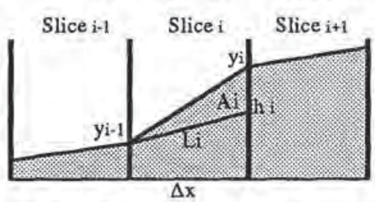

Fig. 5: Considering slices as containers

Let us consider a small change, denoted by ΔW_i, of the mass W_i in slice$_i$. Since $W_i = (y_i+y_{i-1})\gamma\Delta x/2$, we have

(4.1) $$\Delta W_i = (y_i+\Delta y_i+y_{i-1}+\Delta y_{i-1})\gamma\Delta x/2 - (y_i+y_{i-1})\gamma\Delta x/2 = (\Delta y_i+\Delta y_{i-1})\gamma\Delta x/2$$

On the other hand, let us assume that there is a force f_i exerted on the triangle area A_i at the top of slice$_i$, which is parallel to the edge L_i. Due to f_i, A_i tends to move along the direction of f_i at a velocity v_i. The rate of the "flow" of mass of A_i through slice i can be computed by $\gamma A_i v_i/\Delta x$. Thus, the "mass throughput" of slice$_i$ can be quantified by $\gamma A_i v_i \Delta t/\Delta x$, where Δt is a unit of time. Similarly, the mass throughput of slice$_{i+1}$ is given by $\gamma A_{i+1}v_{i+1}\Delta t/\Delta x$.

From the principle of volume conservation, the change of soil quantity in slice$_i$ is the amount of soil which goes out, minus the amount of soil which goes in. It can be expressed by

(4.2) $$\Delta W_i = \frac{\gamma A_i}{\Delta x} v_i \Delta t - \frac{\gamma A_{i+1}}{\Delta x v_{i+1}}\Delta t$$

where $A_i = (y_i-h_i)\Delta x/2$. Putting (4.1) and (4.2) together and rearranging it, we have

(4.3) $$\frac{\Delta y_i}{\Delta t} + \frac{\Delta y_{i-1}}{\Delta t} = \frac{1}{\Delta x}[(y_i-h_i))v_i - (y_{i+1}-h_{i+1}))v_{i+1}]$$

Now let Δt tend to 0. It follows that

(4.4) $$\frac{dy_i}{dt} + \frac{dy_{i-1}}{dt} = \frac{1}{\Delta x}[(y_i-h_i))v_i - (y_{i+1}-h_{i+1}))v_{i+1}]$$

Recall that (3.7) gives us a formula to compute force f_i. From Newton's second law, we have

(4.5) $$f_i = \gamma A_i \frac{dv_i}{dt} = \frac{\gamma\Delta x}{2}(y_i-h_i)\frac{dv_i}{dt}$$

Rearranging, we obtain both

(4.6) $$\frac{dv_i}{dt} = \frac{2f_i}{\gamma\Delta x(y_i-h_i)}$$, and

(4.7) $$v_i = \frac{2}{\gamma\Delta x}\int\frac{f_i}{y_i-h_i}dt$$

Now we take the second derivative of (4.4) with respect to t and plug (4.6) and (4.7) into the resulting formula. That yields

(4.8) $$\frac{d^2y_i}{dt^2} + \frac{d^2y_{i-1}}{dt^2} = \frac{2}{\gamma\Delta x}\left[\frac{dy_i-dh_i}{dt}\int\frac{f_i}{y_i-h_i}dt + f_i - \frac{dy_{i+1}-dh_{i+1}}{dt}\int\frac{f_{i+1}}{y_{i+1}-h_{i+1}}dt + f_{i+1}\right]$$

Note that we can denote h_i and f_i as functions of y_{i-1} and y_i, i.e. $h_i = h(y_{i-1}, y_i)$ and $f_i = f(y_{i-1}, y_i)$, since they can be determined based only on y_{i-1} and y_i if Δx and other soil properties are fixed. Hence, (4.8) is an equation with three variables, namely y_{i-1}, y_i, y_{i+1}. Let us suppose that we have divided the given configuration into n slices. Now we end up with n+1 unknowns, $y_0, y_1, \ldots, y_n$, and n+1 ordinary differential equations involving y_i's, their time derivatives and integrals. Solving these equations, we will obtain the solution for the soil behavior which satisfies both the soil dynamics and the volume conservation.

5. NUMERICAL SOLUTION

In this section we linearize equations (4.8) for both purposes of simplification and discretization. we start from (4.4). Assume that, at any instance of time t_m, velocity v_i of the mass on the top of slice$_i$ is represented by $v_i(t_m)$, the value of y_i is represented by $y_i(t_m)$, the rate of the change of y_i is represented by $y_i'(t_m)=dy_i(t_m)/dt$. Then, at the very next time instance t_{m+1}, the force $f_i=f_i(y_{i-1}(t_m), y_i(t_m))$ can be computed by (3.7) according to the value of y_{i-1} and y_i from the previous step. If the Euler integration algorithm is used, the velocity v_i at the time t_{m+1} can be computed by

$$(5.1) \qquad v_i(t_{m+1}) = v_i(t_m) + \frac{f_i(y_{i-1}(t_m), y_i(t_m))}{W_i}\Delta t$$

where Δt is the integration step size. Similarly $v_{i+1}(t_{m+1})$ is calculated. It follows that, from (4.5), we have

$$(5.2) \qquad y_i'(t_{m+1}) + y_{i-1}'(t_{m+1}) = \frac{1}{\Delta x}[(y_i(t_m)-h(y_{i-1}(t_m),y_i(t_m)))v_i(t_{m+1}) - (y_{i+1}(t_m)-h(y_i(t_m),y_{i+1}(t_m)))v_{i+1}(t_{m+1})]$$

Since at the time instance t_{m+1}, all items on the right hand side are knowns, either from the previous step of the simulation or from the calculations of $v_i(t_{m+1})$ and $v_{i+1}(t_{m+1})$, we may treat it as a constant, namely C_i. We now have n+1 equations in the following format:

$$(5.3) \qquad \begin{aligned} y_0'(t_{m+1}) &= C_0 \\ y_1'(t_{m+1}) + y_0'(t_{m+1}) &= C_1 \\ &\cdots\cdots \\ y_n'(t_{m+1}) + y_{n-1}'(t_{m+1}) &= C_n \end{aligned}$$

Solving (5.3) for $y_i'(t_{m+1})$, i=0, 1, ... n, we will be able to use the Euler method again to determine the new values for each y_i:

$$(5.4) \qquad y_i(t_{m+1}) = y_i(t_m) + y_i'(t_{m+1})\Delta t$$

Algorithm 1 describes the procedure of the numerical solution, in which each step of the algorithm takes linear time to execute. Thus the time complexity of the algorithm is O(n) where n is the number of elevation posts in a given configuration. The space required to store forces, velocities and heights of posts is also proportional to n.

Algorithm 1.

At any time t_{m+1} of simulation, do the following:

1) *for each post y_i, calculate its mass velocity $v_i(t_{m+1})$ by using (5.1);*
2) *for y_i, compute the right hand side of (5.2);*
3) *use forward substitution to solve equations (5.3) for $y_i'(t_{m+1})$, i=0, 1, ... n;*
4) *use Euler integration to determine new value for each $y_i(t_{m+1})$.*

6. EXTENSION TO 3-D

In going to 3-d soil dynamics, we use some essential concepts and results from the discussion on 2-d. First, a given soil configuration is partitioned into small prisms. The values of elevation posts (i.e. vertices) of each prism are evolved by an approximation procedure as follows.

Consider, in Fig. 6, the post z(i,j) chosen arbitrarily:

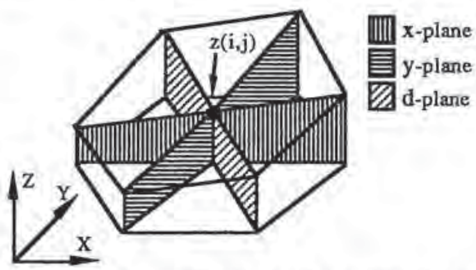

Fig. 6: An approximation of the 3-d configuration

z(i, j) is surrounded by six prisms. At any time instance t, those prisms are the only ones that affect the height of z(i,j). The effect caused by those prisms can be approximated by considering forces exerted on three planes, namely the x-plane, y-plane and d-plane. They are indicated by different types of shaded areas in Fig. 6. Thus the 3-d problem is reduced to a 2-d problem. The finer the partitioning is, the smaller the base triangles of prisms are, and the more accurate the approximation will be.

Let's assume that, at any time t_m, the height of post z(i,j) is represented by $z_{ij}(t_m)$, and the rate of change of z(i,j) is represented by $z_{ij}'(t_m)$. Since $z_{ij}'(t_m)$ is affected by forces from 3 planes, it can be expressed as a summation of three terms:

$$(6.1) \qquad z_{ij}'(t_m) = zx_{ij}'(t_m) + zy_{ij}'(t_m) + zd_{ij}'(t_m)$$

where $zx_{ij}'(t_m)$, $zy_{ij}'(t_m)$ and $zd_{ij}'(t_m)$, are rates of changes of $z_{ij}'(t_m)$ caused by forces exerted on the x-plane, y-plane and d-plane respectively.

During a simulation, each time slice Δt is divided into two substeps $\Delta t1$ and $\Delta t2$. In $\Delta t1$, we first use (3.7) to compute forces exerted on three different planes. Then $zx_{ij}'(t_{m+1})$, $zy_{ij}'(t_{m+1})$ and $zd_{ij}'(t_{m+1})$ can be obtained by solving equations (5.3). In step $\Delta t2$, Euler integration is used to determine new values for each $z_{ij}(t_{m+1})$:

$$(6.2) \qquad z_{ij}(t_{m+1}) = z_{ij}(t_m) + [zx_{ij}'(t_m) + zy_{ij}'(t_m) + zd_{ij}'(t_m)]\Delta t$$

For $\Delta t1$ and $\Delta t2$ of each iteration in the simulation, we split our 2-d computational problem into 3 terms: x-plane scan, y-plane scan and d-plane scan. Each scan has two phases corresponding to two time substeps. A scan on any plane involves calculations of forces exerted on that plane, rates of changes of z(i, j) caused by the forces, new height of each post, etc. Computations for each scan in a time substep are independent of scans on the other planes in the same substep, and therefore can be performed either sequentially or in parallel. It is important to notice that, in the same time substep, scans in different orders (x-scan then y-scan then d-scan, or y-scan then x-scan then d-scan, etc.) will have the same effect. The reasons are discussed in [9].

The 3-d algorithm can be briefly described as follows: Each iteration of simulation is divided into two phases. Steps (1)-(3) of Algorithm 1 are performed first for each scan. Then step (4) is applied for each scan to calculate new values of posts. Both time and space complexity of the 3-d algorithm remain linear in the number of posts.

7. INTERACTION BETWEEN SOIL AND BLADE

In this section, we analyze the interaction between the soil mass and a bulldozer's blade. Let's assume that the height of the blade is H. The shape of the blade can be modeled by an arc of a circle centered at the location $\langle x_c, y_c \rangle$ with radius R. We divide the arc into n segments, each of which has length $R\Delta\beta$. Furthermore, the soil mass in front of the blade is also partitioned into n slices by horizontal lines at each joint point of two arc segments as shown in Fig. 7.

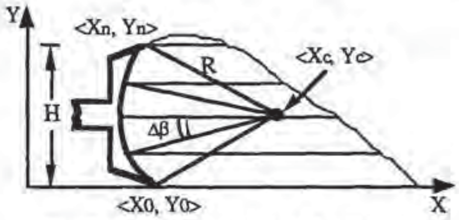

Fig. 7: Dividing the blade and soil mass

To calculate the force resisting cutting, we arbitrarily pick the i-th slice from the partitioning. The arc segment can be approximated by a line segment from point $\langle x_i, y_i \rangle$ to point $\langle x_{i+1}, y_{i+1} \rangle$. Note that the length of the line segment, denoted by ΔL, approaches the length of the arc when $\Delta\beta$ approaches 0. The idea is explained in Fig. 8:

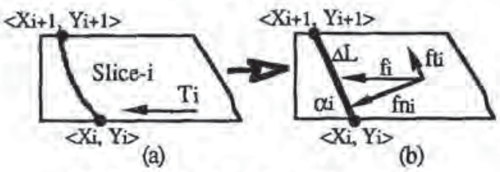

Fig. 8: Free body diagram for i-th slice

If the cutting part of the bulldozer pushes the soil mass with enough force, the equilibrium will be destroyed. At this moment, the resistance parallel to blade motion at the point $\langle x_i, y_i \rangle$ can be calculated by the formula [1]:

$$(7.1) \qquad T_i = Ae^{2\alpha_i + B}[\gamma(H + y_0 - y_i) + c\cot(\phi)]\tan(\phi)$$

where T_i is the localized shear stress and α_i is the magnitude of the angle of inclination of ΔL to the horizon. The remaining symbols are as explained earlier. All angles are given in radians. Constants A and B are only related to ϕ and δ (δ is the angle of external friction), of the given soil:

$$(7.2) \qquad A = \frac{\sin(\delta)\,[\,\cos(\delta) + \sqrt{\sin^2(\phi) - \sin^2(\delta)}\,]}{1 - \sin(\phi)}$$

$$(7.3) \qquad B = \delta + \sin^{-1}\left(\frac{\sin(\delta)}{\sin(\phi)}\right) - \pi$$

Due to different cutting depths (given by $H+y_0-y_i$) and different inclination angles α_i, the magnitudes of T_i vary. The resistance force exerted on ΔL can be computed by $f_i = T_i\,\Delta L$. As shown in Fig. 8-(b), f_i can be further decomposed into two components, one normal to ΔL and another parallel to ΔL. The normal force is cancelled by the opposite force contributed by ΔL. The parallel force has the following property: In the upper portion of the blade, it has a smaller magnitude and points in the negative y-direction. In the lower portion, it has a larger magnitude and points in the positive y-direction. Let fy_i be the y component of the parallel force. It can be computed by:

$$(7.4) \qquad fy_i = (C_1 - C_2 y_i)\,e^{2\alpha_i}\sin(\alpha_i)\cos(\alpha_i)\,\Delta L$$

where $C_1 = Ae^B[\gamma(H+y_0)\tan(\phi) + c]$ and $C_2 = Ae^B\gamma\tan(\phi)$.

Now we calculate the summation of all fy_i's, represented by F^y, which gives us the total force pushing the soil mass in front of the blade upwards.

$$(7.5) \qquad F^y = \frac{1}{2}\sum_{i=1}^{n}(C_1 - C_2 y_i)\,e^{2\alpha_i}\sin(2\alpha_i)\,\Delta L$$

To get an accurate solution, we let $\Delta\alpha$ approach 0. In this case we have the following equations [9]:

$$(7.6) \qquad \alpha_i = \alpha_0 + i\,\Delta\alpha$$

$$(7.7) \qquad \lim_{\Delta\alpha \to 0} \Delta L = R\,\Delta\alpha$$

$$(7.8) \qquad \lim_{\Delta\alpha \to 0} y_i = y_c - R\cos(\alpha_0 + i\,\Delta\alpha)$$

Replacing α_i, ΔL and y_i in (7.5) by right hand sides of above equations and making $\Delta\alpha$ infinitesimal, we obtain:

$$(7.9) \qquad F^y = \frac{R}{2}\int_{\alpha_0}^{\alpha_n}[C_1 - C_2 y_c + C_2 R\cos(\alpha)]\,e^{2\alpha}\sin(2\alpha)\,d\alpha$$

To simulate cases in which the blade are not fully loaded, we fix the lower bound angle of the definite integral and keep the upper bound angle changing from α_0 to α_n. That will give us the following figure:

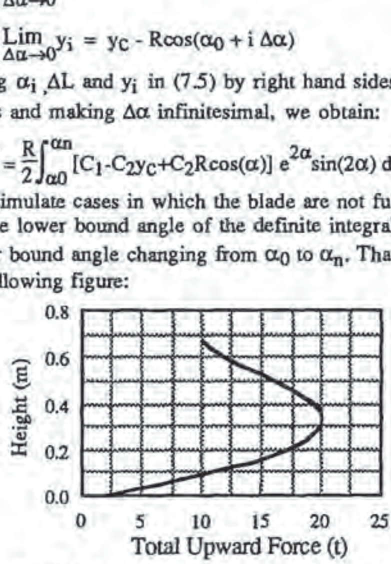

Fig. 9: Total upward force along the blade

In Fig 9, the vertical axis indicates y coordinates of points up to which the soil is loaded and the horizontal axis gives F^y under the given configuration. The data is recorded with α_0=1.22, R=100cm, c=1.9, δ=0.5, ϕ=0.54 and γ=2.0 (angles are measured in radius). For example, if the soil is loaded up to the middle point of the height of the blade, i.e. y=36.0 cm, the curve shows that at this point the total upward force reaches its maximum (about 20 metric tons).

The analysis shows that the total force is always positive. That is, the soil mass being cut always moves upward along the blade. This phenomenon is also observed experimentally [1]. The sequence of events occurring during the process of interaction between the cutting blade and the excavated soil before the blade can be described by 3 steps. 1) the soil chip being cut from the main soil mass moves upward along the blade because of resistance to the soil. 2) the soil chip is broken up into individual lumps on the upper part of the blade. 3) These lumps move downward toward the soil layers being further cut and from the soil prism which is being dragged. This phenomenon is depicted by Fig. 10:

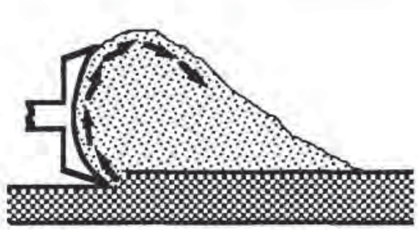

Fig. 10: Pattern of soil movement ahead of the blade

8. SOIL IN A BUCKET

In this section, we present a graphical model of a scooploader. For clarity, we assume that only buckets which can be represented by convex polygons will be processed. Again we first divide the soil configuration and the bucket into n slices with equal width Δx. This is shown in Fig 11, where the thick line segments indicate the bucket:

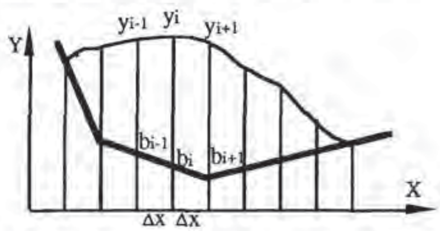

Fig. 11: Dividing the soil mass in a bucket

The motion of the soil mass in the bucket is a combination of two movements: 1) the movement of a portion of the given soil mass along a potential failure plane on the top; and 2) the whole mass along the bucket surface. We will refer to these motions as *local movement* and *global movement* respectively. In general, a local movement is caused by an unstable configuration of the given soil, while a global movement is due to the shear stress experienced by a surface of the soil mass in contact with the bucket. This can be seen more clearly through the free body diagram of slice-i arbitrarily picked from the partitioning (see Fig. 12), where f_i is the force driving a local movement along the failure plane denoted by line segment $<y_{i-1}, h_i>$. This force can be quantified by (3.7).

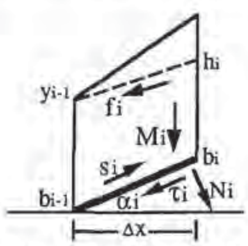

Fig. 12: Analyzing forces of slice-i

Let's now consider the global movement. The driving force, denoted by G, can be calculated by analyzing the free body diagram of each free body. As shown in Fig. 12, the weight M_i of slice-i can be decomposed into two elements: the shear stress force τ_i and the normal stress force N_i. N_i is canceled by the opposite force provided by the bucket surface $<b_{i-1}, b_i>$. τ_i is the force which pushes the mass to move along the bucket surface. The shear strength force s_i, on the other hand, resists the shear displacement of soil particles along the bucket surface. These forces can be determined from the Mohr-Coulomb theory as indicated by [5]:

(8.1) $\tau_i = M_i \sin(\alpha_i)$

(8.2) $s_i = cL_i + M_i \cos(\alpha_i) \tan(\delta)$

where c is the coefficient of cohesion, δ is the angle of external friction, L_i is the length of the line segment from b_{i-1} to b_i, M_i is the weight of slice-i, and α_i is the angle between the bucket surface and the horizontal. δ indicates a measure of the friction between soil and the surface of the bucket. It is given in radians. For loamy clay and sand, the typical values of δ are 18 and 30 respectively [1]. The units of these symbols are as explained earlier.

For equilibrium consideration, we use a method similar to the one described in [6]. The stress force τ and the strength force s can be expressed by vectorial summations:

(8.3) $\tau = \sum_{i=1}^{n} \tau_i = \sum_{i=1}^{n} M_i \sin(\alpha_i) <\cos(\alpha_i), \sin(\alpha_i)>$

(8.4) $s = \sum_{i=1}^{n} s_i = \sum_{i=1}^{n} M_i \cos(\alpha_i) \tan(\delta) <\cos(\alpha_i), \sin(\alpha_i)>$

Note that the term cL_i is dropped from(8.4), since the cohesion coefficient c describes molecular attraction among like particles and is zero between soil and a bucket surface. Thus, the safety factor F_s can be defined as

(8.5) $F_s = \dfrac{|s|}{|\tau|}$

When F_s is less than one, sliding of the whole mass along the bucket surface is inevitable. In this case, the total driving force G of the global movement can be computed by

(8.6) $G = \begin{cases} \tau - s, & \text{if } \tau > 0 \\ \tau + s, & \text{otherwise} \end{cases}$

In order to simulate the movement of soil mass in a bucket, we decompose G to smaller components which are parallel to the bucket surface. These component forces are distributed to slices so that the dynamics of soil can be considered individually for each slice. After carefully analyzing the behavior of the soil mass, we know that the following constraints must be satisfied:

1) The summation of component forces should equal G;
2) All slices should have the same x-acceleration.

The first constraint is obvious. The second one should be always true simply because: 1) a bucket always has a convex shape; and 2) some slices would fall apart and tension cracks or deformation would occur if the x components of their accelerations are different.

Let $G^x = G\cos(\alpha)$ and $G^y = G\sin(\alpha)$ be the x and y components of G respectively, where α is the angle between the vector G and the horizontal. Let g_i be a component force of G, which is experienced by the bucket surface of i-th slice. From the constraints we have

(8.7) $G \cos(\alpha) = \sum_{i=1}^{n} g_i \cos(\alpha_i)$

(8.8) $G \sin(\alpha) = \sum_{i=1}^{n} g_i \sin(\alpha_i)$

(8.9) $\dfrac{g_1}{M_1}\cos(\alpha_1) = \dfrac{g_2}{M_2}\cos(\alpha_2) = \cdots = \dfrac{g_n}{M_n}\cos(\alpha_n)$

(8.7)–(8.9) give us n+1 equations with n+1 unknowns, namely $g_1, g_2, \ldots g_n$ and α. Other variables can be computed according to the geometry of the given configuration. Solving the equations we obtain

$$(8.10) \quad g_i = \frac{M_i \cos(\alpha)}{M \cos(\alpha_i)} G, \qquad \text{for } i = 1, 2, \ldots, n.$$

where $\alpha = \tan^{-1}(\frac{1}{M}\sum_{i=1}^{n} M_i \tan(\alpha_i))$.

Having f_i and g_i computed, we model the soil dynamics in a bucket by using Algorithm 1 to evaluate simultaneous equations in (5.3). In order to do so, we simply replace f_i by f_i+g_i when calculating the rate of changes of each post at the time t_{m+1}. The rest of the algorithm remains unchanged.

9. IMPLEMENTATIONS

9.1 IMPLEMENTATION OF A BULLDOZER

Recall that the terrain surface is represented by a regular tessellation model. An array, namely z, of size m×n is used to store the height of elevation posts. An element z(i,j) in the array represents the elevation at the location <i,j>.

As mentioned in section 7, an excavating process of a bulldozer can be separated into three phases. These actions can be simulated by an algorithm with three corresponding stages: digging, piling and soil slipping. First, the algorithm keeps track of the motion of the blade. If the altitude value of the bottom of the blade is denoted by b(i,j) at the location <i,j>, then any elevation post z(i,j) passed through by b(i,j) are forced to have the same value. This procedure will create a ditch along the path of the bulldozer on the terrain surface.

The second stage models the upward movement of the soil along the blade. Let P be a set of soil prisms which have been passed through by the blade in the last time step. Let $z_p(i,j)$, $z_q(i,j)$ and $z_r(i,j)$ be surrounding posts of a prism p(i,j). The amount of soil contributed by prisms in P to the soil chip moving upwards can be computed by:

$$(9.1) \quad V = \frac{\Delta x \Delta y}{6} \sum_{p(i,j) \in P} \Delta V(i,j)$$

where

$$\Delta V(i,j) = z_p(i,j)+z_q(i,j)+z_r(i,j) - b_p(i,j)-b_q(i,j)-b_r(i,j)$$

Finally, in the third stage the amount of soil computed by (9.1) is put in front of the blade. Since the height that the soil is lifted upward along the blade and the speed in which the soil chips are broken into individual lumps depend on the cohesion property of the given soil, the procedure can be simulated by spreading the soil to a chunk shown below:

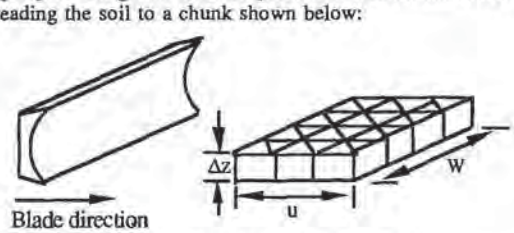

Fig. 13: Dimensions of soil chunk

The dimensions of the soil chunk are determined according to the following equation:

$$(9.2) \quad \Delta z = \kappa\,(1+c)$$
$$u = \frac{V}{w\,\kappa\,(1+c)}$$

where V is the total volume calculated by (9.1), w the width of the blade, c the cohesion coefficient, and κ a constant which determines how far forward the soil chip moves during one time step. In the implementation, κ is chosen experimentally to make the simulation looks more realistic.

After all this is done, Δz is added to the elevations of corresponding posts, and the slippage model introduced in previous sections is used to simulate the free flow motion of broken lumps of soil. It should be mentioned that the soil being brought to the top of the berm arrives continuously in the real world. However, with a discrete time simulation process, the chunk is a reasonable representation of the amount and location of the soil that would really arrive during one time step. The slippage model smoothly integrates this chunk into the berm, resulting in a realistic appearance.

Another important phenomena associated with physical properties of soil is swelling, which is due to a number of reasons: 1) the affinity of the soil for water; 2) the base exchange behavior and electrical repulsion; and 3) the expansion of entrapped air within the soil mass [4]. The model simulating the expansion of excavated soil is also discussed and implemented in [9].

9.2 IMPLEMENTATION OF A BUCKET

In implementing a 3-d bucket, we first divide it into m×n cross sections in a way such that they are parallel to either the x-z plane or the y-z plane. We refer to these sections as x-sections and y-sections respectively. The result of the division is shown in Fig. 14, where an x-section and a y-section are emphasized by two shaded polygons.

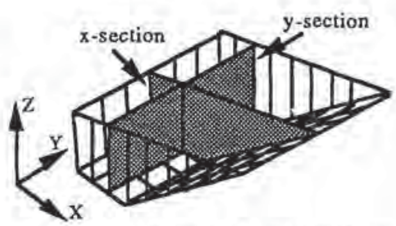

Fig. 14: Dividing a bucket into sections

Therefore, the 3-d soil dynamics in a bucket is reduced to m×n 2-d cases. For each individual cross section, we further partition a 2-d soil configuration into soil slices (see Fig. 11.). The soil dynamics of each slice is handled by means of the technique introduced in section 8.

A simulation procedure can be described as follows: Each iteration of a simulation can be accomplished by two steps. The first step computes forces for each soil slice of every bucket section according to (5.3) and (8.10). The second step uses the Euler integration method to determine new values for each elevation post (see Algorithm 1). These posts are intersections of x-sections and y-sections.

The cutting and loading activities of a scooploader can be modeled by a method similar to the one presented in section 7. The discussion, therefore, is omitted.

10. CONCLUSION AND FUTURE WORK

Experimental realtime models of a bulldozer and a scooploader have been implemented in the c programming language. Both time and space costs of algorithms are linear in the size of the bulldozer's blade, the size of the bucket and the resolution of the ground mesh. The simulations were done on a Silicon Graphics 4D/240 GTX computer. When using 4 processors, two bulldozers run at 6-8 frames/second. The scooploader model uses 2 processors, running at 10-15 frames per second. The number of elevation posts to model the ground for both models is 90×90. The simulations look very realistic.

Future research work may include soil compressibility and moisture content. The compression of soil layers is due to deformation and relocation of soil particles and expulsion of air or water from the void spaces [6]. Fundamental principles for estimating settlements of soil under superimposed loading should be explored so it can be used to provide vehicle tracks or conduct trafficability studies. The moisture content of the soil affects its unit weight and cohesion and results in different behaviors. Those properties should be incorporated into analytical models to provide more realistic simulations.

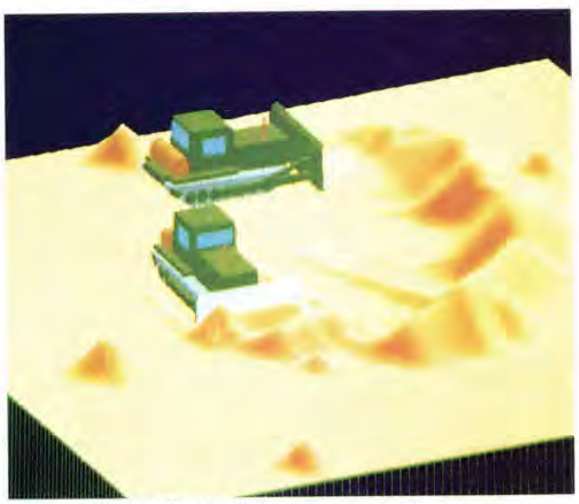

Fig. 15: Two bulldozers are at a work scene

Fig. 16: A scooploader is loading

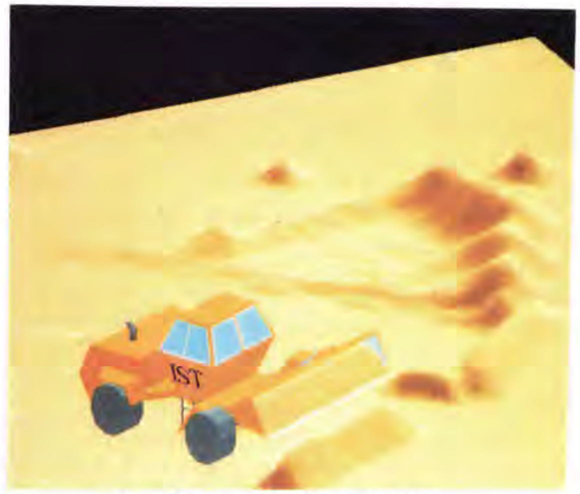

Fig. 17: A scooploader is dumping

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Turbulent Wind Fields for Gaseous Phenomena

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Abstract

The realistic depiction of smoke, steam, mist and water reacting to a turbulent field such as wind is an attractive and challenging problem. Its solution requires interlocking models for turbulent fields, gaseous flow, and realistic illumination. We present a model for turbulent wind flow having a deterministic component to specify large-scale behaviour, and a stochastic component to model turbulent small-scale behaviour. The small-scale component is generated using space-time Fourier synthesis. Turbulent wind fields can be superposed interactively to create subtle behaviour. An advection-diffusion model is used to animate particle-based gaseous phenomena embedded in a wind field, and we derive an efficient physically-based illumination model for rendering the system. Because the number of particles can be quite large, we present a clustering algorithm for efficient animation and rendering.

CR Categories and Subject Descriptors: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism; I.3.3 [**Computer Graphics**]: Picture/Image Generation; G.3 [**Probability and Statistics**]: Probabilistic algorithms.

Additional keywords and phrases: turbulent flow, stochastic modelling, Kolmogorov energy spectrum and cascade, transport model of illumination, Fourier synthesis, advection-diffusion, gaseous phenomena.

1 Introduction

We have come to appreciate the central role that irregularity plays in modelling the shape of natural objects. The analogue for wind and fluids is *turbulence*, and its effects are no less essential to the realistic portrayal of gaseous natural phenomena: curling wisps of smoke, mist blowing across a field, car exhaust, an aerosol spray, steam rising from a coffee mug, clouds forming and moving across the sky, the fall of leaves, a swirl of dust in a room, a hurricane. These effects are caused by the interaction of objects with a wind velocity field. Modelling the effect of wind requires that we model both the wind field and this interaction. Both Sims [14] and Wejchert and Haumann [17] model a wind field as the superposition of deterministic fields. Modelling a visually convincing turbulent wind field this way is painstaking. The greatest success in this direction was the particle-based "Blowing in the Wind" animation by Reeves and Blau [10].

Stochastic modelling is a natural alternative strategy. In [13], Shinya and Fournier describe an approach developed independently of ours but which has some similarities. They employ stochastic processes and Fourier synthesis to derive a wind field in spatiotemporal frequency domain, and invert the result to get a periodic space-time wind field. We employ the same paradigm, but our model and application are quite different. Although both wind models can be applied to a wide range of phenomena, and [13] demonstrates this very well, their main concern is with coupling the wind model to macroscopic physical models of rigid or deformable objects, whereas we are mostly concerned with microscopic interaction with gaseous and fluid phenomena. Consequently, our model of turbulence is dissimilar: Shinya and Fournier assume a constant deterministic temporal evolution (Taylor Hypothesis), while for us temporal evolution is also a stochastic process. Our wind model also differs in that an animator has direct control over deterministic and stochastic components of a field.

In this paper, turbulent wind fields are modelled as stochastic processes. The model is empirically plausible[5]. A wind field is generated from large-scale motion and from the statistical characteristics of the small turbulent motion, both freely chosen by an animator. This is analogous to modelling rough terrain by providing the global shape as given by a set of height samples, and the desired roughness of the terrain [2]. The large scale of the wind field will be modelled using simple wind field primitives [14, 17]. The small scale of the wind field will be modelled as a three-dimensional random vector field varying over space and time. This field is generated using inverse an FFT method[16] that we have generalized to a vector field. The resulting wind field has two desirable properties. First, it is periodic and is thus defined for any point in space-time. Second, it is generated on a discrete lattice and can be interactively calculated using four-linear interpolation.

Gases have been modelled in several ways. Ebert models a gas as a solid texture. With some trial-and-error (and in our experience, significant human effort), realistic animations were obtained[1]. Sakas models a gas as a 3-D random density field, generating it using spectral synthe-

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sis [12]. While spectral synthesis is useful in generating turbulent wind fields, it is not ideal for directly generating density fields: visual artifacts appear due to the periodicity of the field and the entire density field must be computed at once. The temporal evolution of the density field is limited to simple translations. Both of the above models are computationally expensive to visualize, and hence interactive modelling is not feasible. Using physically-based turbulence to animate density fields is mathematically nontrivial, but we shall show that this can be done efficiently.

We model gases as density distributions of particles. The evolution of a density distribution within our wind field is described by an advection-diffusion equation. We efficiently solve this equation by modelling the gas as a "fuzzy blobby" with time varying parameters. A fast ray-tracing algorithm is used, based on a front to back single-scattering illumination model, to render such a density distribution.

2 A Multiple-Scale Wind Field Model

Physically, wind fields are the result of the variations of the velocity $\mathbf{u}(\mathbf{x},t)$ and the pressure $p(\mathbf{x},t)$ of a fluid (including air) over space and time. These variations are caused by various forces: external forces $\mathbf{F}$ applied to the fluid, non-linear interactions between different modes of the velocity field and viscous dissipation at a rate ν. By summing these forces and equating them to the acceleration of the fluid we obtain the Navier-Stokes equations:

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u}\cdot\nabla)\mathbf{u} - \frac{1}{\rho_f}\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{F}, \qquad (1)$$

where ρ_f is the density of the fluid. If the velocities of the fluid are much smaller than the speed of sound, we can assume that the fluid is incompressible [5], i.e.,

$$\nabla\cdot\mathbf{u} = 0. \qquad (2)$$

When proper initial conditions and boundary conditions are specified, Eqs. 1 and 2 are sufficient to solve for the velocity field and the pressure of the fluid for any time instant.

The above equations could be used to animate realistic wind fields. One would first specify the physical properties of the fluid that make up the model, including an initial velocity field and boundary conditions. One would then control the fluid motion by applying external forces. Realistic wind fields would be obtained by solving the Navier-Stokes equations as needed. This is entirely akin to the control problem for articulated figures, and it shares the same difficulties. First, a desired effect is hard to achieve by "programming" it using only external forces. Second, the non-linearities present in the Navier-Stokes equations make them hard to solve numerically, especially in the presence of turbulence (low viscosity). Linearizing the equations can improve stability and efficiency, which has been done by Kass and Miller to model the surface of water [4]. This results in highly viscous fluids that do not exhibit turbulence.

We shall model a turbulent wind field by separating it into a large-scale component $\mathbf{u}_l$ and a small scale component $\mathbf{u}_s$. The large-scale term is composed of simple wind fields, resulting in very viscous fluids. The small-scale term is a random field. We shall make a useful but physically implausible assumption that the components are independent, that is, that large scales do not affect the small scales and vice-versa. Hence we will write

$$\mathbf{u}(\mathbf{x},t) = \mathbf{u}_l(\mathbf{x},t) + \mathbf{u}_s(\mathbf{x},t). \qquad (3)$$

This assumption permits the real-time simulation and independent control of both large-scale and small-scale effects. The results, as we shall see, are quite convincing. We shall further discuss this assumption in our conclusions.

3 Small Scale Modelling

3.1 Random Vector Fields

In this section we will denote the small scale component $\mathbf{u}_s$ simply by $\mathbf{u}$. It is defined as a random space-time vector field, a function that assigns a random velocity to each point $(\mathbf{x},t)$ in space-time [15]. We shall invoke the standard Gaussian assumption [7]: that the random vector field is entirely determined by its second-order moments. These moments are obtained by statistically averaging (denoted by $\langle\ \rangle$) components of the evolving random velocity field. We will assume that the mean values of each component $\mu_i(\mathbf{x},t) = \langle u_i(\mathbf{x},t)\rangle$ $(i=1,2,3)$ of $\mathbf{u}$ are constant and equal to zero. The *cross-correlation* between different components of the velocity field at two different points in space-time $(\mathbf{x},t)$ and $(\mathbf{x}',t')$ are given by the functions

$$\Gamma_{ij}(\mathbf{x},t;\mathbf{x}',t') = \frac{\langle u_i(\mathbf{x},t)u_j(\mathbf{x}',t')\rangle}{\langle \mathbf{u}^2\rangle}, \quad i,j=1,2,3. \qquad (4)$$

Where $\langle \mathbf{u}^2\rangle = \langle u_1^2 + u_2^2 + u_3^2\rangle$ denotes the variance of the velocity field and physically is equal to twice the kinetic energy of the field. We will assume that the velocity field is *homogeneous* in space and *stationary* in time, which means that the cross-correlation only depends on the difference $\mathbf{r} = \mathbf{x}'-\mathbf{x}$ between the two points and the difference $\tau = t'-t$ between the two times: $\Gamma_{ij}(\mathbf{x},t;\mathbf{x}',t') = \Gamma_{ij}(\mathbf{r},\tau)$.

Homogeneous velocity fields have a corresponding representation in spatial-frequency domain via a spatial Fourier transform. Intuitively this transformation can be thought of as a decomposition of the velocity field into "eddies" of different sizes: large eddies correspond to small spatial frequencies and conversely for small eddies. The stationarity of the velocity field allows it to be represented in frequency domain by a temporal Fourier transform. We will denote spatial frequencies by $\mathbf{k} = (k_1,k_2,k_3)$ and temporal frequencies by ω.[1] We represent the velocity field in frequency domain via the usual Fourier transform:

$$\hat{\mathbf{u}}(\mathbf{k},\omega) = \int\int \mathbf{u}(\mathbf{x},t)\exp(-i\mathbf{k}\cdot\mathbf{x} - i\omega t)\,d\mathbf{x}dt. \qquad (5)$$

Writing the transform in this manner facilitates its separation into spatial and temporal frequency components. The Fourier-domain equivalent of the cross-correlation functions are the cross-spectral density functions:

$$\Phi_{ij}(\mathbf{k},\omega) = \langle \hat{u}_i^*(\mathbf{k},\omega)\hat{u}_j(\mathbf{k},\omega)\rangle, \quad i,j=1,2,3, \qquad (6)$$

where the "$*$" denotes the complex conjugation. Conveniently for us, the cross-spectral density functions and the cross-correlation functions are Fourier-transform pairs [15].

Finally, we assume that the velocity field is spatially *isotropic*, meaning that the cross-correlation functions are invariant under rotations. Thus the cross-correlation functions only depend on the distance $r = \|\mathbf{r}\|$ between two points. Isotropy and incompressibility (Eq. 2) imply that the cross-spectral density functions are of the form [5]

$$\Phi_{ij}(\mathbf{k},\omega) = \frac{E(k,\omega)}{4\pi k^4}(k^2\delta_{ij} - k_ik_j), \quad i,j=1,2,3, \qquad (7)$$

[1] In the turbulence literature, the term *wave number* is often used instead of *spatial frequency*. We will use *spatial frequency*, which is more common in computer graphics, but we shall denote spatial frequencies by $\mathbf{k}$, reserving the letter ω for temporal frequencies.

where δ_{ij} is the *Kronecker delta*, k is the length of the spatial frequency $\mathbf{k}$ and E is a positive function called the *energy spectrum function*. Its physical interpretation is that it gives the contribution of all spatial frequencies of length k and frequency ω to the total kinetic energy of the velocity field:

$$\frac{1}{2}\langle \mathbf{u}^2 \rangle = \int_0^\infty \int_{-\infty}^{\infty} E(k,\omega)\, d\omega\, dk. \qquad (8)$$

3.2 The Energy Spectrum Function

Eq. 7 states that the structure of a velocity field (via its cross-spectral density functions) is entirely determined by its energy spectrum function. In other words, an animator can control the qualities of turbulent motion by specifying the shape of the energy spectrum. This function can be arbitrary as long as the integral of Eq. 8 exists. In the turbulence literature one can find a wide variety of different energy spectra for various phenomena. These models are either determined from experimental data or obtained from simplifying assumptions about the fluid. The best-known example of the latter for turbulence that has reached a steady-state (i.e., $\int_{-\infty}^{\infty} E(k,\omega)\, d\omega \rightarrow E(k)$) is the *Kolmogorov energy spectrum* [5]:

$$E_K(k) = \begin{cases} 0 & \text{if } k < k_{\text{inertial}} \\ 1.5\, \epsilon^{2/3}\, k^{-5/3} & \text{otherwise} \end{cases} \qquad (9)$$

This spectrum results from an *energy cascade*, where energy introduced at frequency k_{inertial} is propagated to higher frequencies at a constant rate ϵ. Instead of invoking Taylor's Hypothesis [13] we model the temporal frequency dependence of the energy spectrum function $E(k,\omega)$ by multiplying the Kolmogorov energy spectrum $E_K(k)$ by a temporal spread function $G_k(\omega)$ subject to:

$$\int_{-\infty}^{\infty} E(k,\omega)\, d\omega = E_K(k) \int_{-\infty}^{\infty} G_k(\omega)\, d\omega = E_K(k). \quad (10)$$

This guarantees conservation of kinetic energy (cf. Eq. 8). Furthermore, we want the small eddies to be less correlated in time than the large eddies. Spatially, this means that small eddies spin, ebb and flow more quickly than large eddies; this behaviour can be observed when watching a water stream or smoke rising from a cigarette. We can achieve this behaviour by setting G_k to a Gaussian with a standard deviation proportional to k:

$$G_k(\omega) = \frac{1}{\sqrt{2\pi}\, k\sigma} \exp\left(-\frac{\omega^2}{2k^2\sigma^2} \right). \qquad (11)$$

Indeed, for large eddies (as $k \rightarrow 0$), G_k is a spike at the origin, corresponding to the spectral distribution of a highly-correlated signal; for small eddies (as $k \rightarrow \infty$) the spectral density becomes constant, denoting an uncorrelated signal.

3.3 Generating the Small Scale Component

We now describe an algorithm to generate a random velocity field having specified cross-spectral density functions Φ_{ij}. The algorithm is a generalization of Voss's inverse FFT method[16]. The idea is to filter an uncorrelated white noise velocity field in the Fourier domain, and then to take an inverse Fourier transform to obtain the desired random velocity field. The challenge is thus to find the right filter such that the resulting velocity field has the desired statistics.

We first compute the velocity field in the frequency domain for discrete spatial frequencies (i,j,k) and temporal frequencies l.[2] Let us assume that the discretization is uniform and that there are N samples per dimension. Then the discrete Fourier transform (DFT) of the velocity field $\hat{\mathbf{u}}_{i,j,k,l}$ is defined on a discrete lattice of size $3N^4$. To ensure that the resulting space-time velocity field is real valued, the elements of the DFT must satisfy the following symmetries: $\hat{\mathbf{u}}_{i,j,k,l} = \hat{\mathbf{u}}^*_{N-i,N-j,N-k,N-l}$, where the indices are taken modulo N, i.e., $N - 0 = 0$[9]. In the special case when the indices on both sides of the equality are identical (e.g., $\hat{\mathbf{u}}_{N/2,0,N/2,N/2}$) we have to set the imaginary parts of $\hat{\mathbf{u}}_{i,j,k,l}$ to zero. The following algorithm generates a DFT with the required properties.

for i,j,k,l in $\{0,\ldots,N/2\}$ do
  compute $\hat{\mathbf{u}}_{i,j,k,l}$, $\hat{\mathbf{u}}_{N-i,j,k,l}$, $\hat{\mathbf{u}}_{i,N-j,k,l}$, $\hat{\mathbf{u}}_{i,j,N-k,l}$,
    $\hat{\mathbf{u}}_{i,j,k,N-l}$, $\hat{\mathbf{u}}_{N-i,N-j,k,l}$, $\hat{\mathbf{u}}_{N-i,j,N-k,l}$, $\hat{\mathbf{u}}_{N-i,j,k,N-l}$
  $\hat{\mathbf{u}}_{N-i,N-j,N-k,N-l} = \hat{\mathbf{u}}^*_{i,j,k,l}$
  $\hat{\mathbf{u}}_{i,N-j,N-k,N-l} = \hat{\mathbf{u}}^*_{N-i,j,k,l}$
  $\hat{\mathbf{u}}_{N-i,j,N-k,N-l} = \hat{\mathbf{u}}^*_{i,N-j,k,l}$
  $\hat{\mathbf{u}}_{N-i,N-j,k,N-l} = \hat{\mathbf{u}}^*_{i,j,N-k,l}$
  $\hat{\mathbf{u}}_{N-i,N-j,N-k,l} = \hat{\mathbf{u}}^*_{i,j,k,N-l}$
  $\hat{\mathbf{u}}_{i,j,N-k,N-l} = \hat{\mathbf{u}}^*_{N-i,N-j,k,l}$
  $\hat{\mathbf{u}}_{i,N-j,k,N-l} = \hat{\mathbf{u}}^*_{N-i,j,N-k,l}$
  $\hat{\mathbf{u}}_{i,N-j,N-k,l} = \hat{\mathbf{u}}^*_{N-i,j,k,N-l}$
end for

for i,j,k,l in $\{0,N/2\}$ do
  set imaginary parts of $\hat{\mathbf{u}}_{i,j,k,l}$ to zero
end for

To compute each element $\hat{\mathbf{u}}_{a,b,c,d}$ in the first loop, three independent complex random variables $X_m = r_m e^{2\pi i\theta_m}$ $(m = 1,2,3)$ are generated with normally distributed gaussian random amplitudes r_m and with uniformly distributed random phases θ_m. The components of that element are then calculated as

$$\begin{aligned} (\hat{u}_1)_{a,b,c,d} &= \hat{h}_{11}((i,j,k),l)X_1, \\ (\hat{u}_2)_{a,b,c,d} &= \hat{h}_{21}((i,j,k),l)X_1 + \hat{h}_{22}((i,j,k),l)X_2, \\ (\hat{u}_3)_{a,b,c,d} &= \hat{h}_{31}((i,j,k),l)X_1 + \hat{h}_{32}((i,j,k),l)X_2 + \\ &\quad \hat{h}_{33}((i,j,k),l)X_3. \end{aligned}$$

The functions $\hat{h}_{mn}$ are derived from the cross-spectral density functions as shown in Appendix A (Eq. 21). The velocity field is then obtained by taking three inverse DFT's:

$$\begin{aligned} u_1 &= \text{invFFT4D}(\hat{u}_1) \\ u_2 &= \text{invFFT4D}(\hat{u}_2) \\ u_3 &= \text{invFFT4D}(\hat{u}_3). \end{aligned}$$

The resulting velocity field is defined on a discrete lattice and is periodic in space and time. Thus even a small lattice defines a field everywhere in space-time. The spacing of this grid determines the smallest scale of the turbulence.

4 Animation of Gaseous Phenomena

Physically a gas is composed of many particles. We could therefore animate a gas by moving its particles about the wind field, but this would require a vast set of particles. We shall instead consider the *density* $\rho(\mathbf{x},t)$ of particles at space-time point $(\mathbf{x},t)$. Assuming that the particles have no effect on the wind field, the evolution of the density distribution is given by an *advection-diffusion* (A-D) equation

[2] The choice of i,j,k here as indices should not be confused with their different use above.

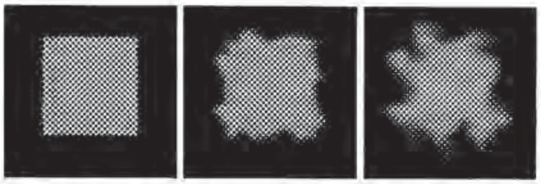

Figure 1: Evolution of a density distribution

[5] to which we have added a dissipation term:

$$\frac{\partial \rho}{\partial t} = -\mathbf{u}\nabla\rho + \kappa\nabla^2\rho - \alpha\rho. \quad (12)$$

The first term on the right hand side is the advection term that accounts for the effects of the wind field on the density. The second term accounts for molecular diffusion at rate κ. This term can also be used to model turbulent diffusion from scales smaller than the smallest scale of the modelled turbulence. The third term accounts for dissipation of density at rate α. Since the velocity $\mathbf{u}$ is given, the equation is linear in ρ and can be solved by finite differences. The density distribution is then resolved on a finite grid and can be rendered using an efficient voxel-based volume renderer [1, 6]. Figure 1 depicts the evolution of an initially square distribution evolving under the influence of a two-dimensional wind field calculated using a standard PDE solver [9]. Computations for four-dimensional wind fields become rapidly prohibitive both in computation time and memory. To obtain tractable animations we propose an alternative strategy. We shall assume that the density distribution is a weighted sum of a simple distribution f:

$$\rho(\mathbf{x},t) = \sum_{i=1}^{n} m_i(t) f(\|\mathbf{x}-\mathbf{x}_i(t)\|, t-t_i) = \sum_{i=1}^{n} \rho_i(\mathbf{x},t). \quad (13)$$

In other words the density distribution is a "fuzzy blobby" with time-dependent field function f, where $\mathbf{x}_i(t)$ is the centre of mass, t_i is the time at which the "blob" ρ_i is created and $m_i(t)$ is its mass. If we suppose that f is a gaussian distribution with a standard deviation σ_0 much smaller than the smallest scale of the turbulent wind field, the wind field can be assumed to be constant on each blob. The advection term therefore only moves the blob, but does not deform its shape. The movement of the blob is hence given by integrating its centre of mass over the wind field:

$$\mathbf{x}_i(t) = \mathbf{x}_i(t_i) + \int_{t_i}^{t} \mathbf{u}(\mathbf{x}_i(s), s)\, ds, \qquad i = 1, \cdots, n. \quad (14)$$

The deformation of the shape of the blob is given by the diffusion term. Here we note that the diffusion at rate κ after time $t - t_i$ of a gaussian with variance σ_0^2 is equivalent to convolving a gaussian of variance $\kappa(t - t_i)$ with a gaussian of variance σ_0^2 (cf. [18]). Gaussians are closed under convolution, and the resulting gaussian has variance $\sigma_i^2(t) = \sigma_0^2 + \kappa(t - t_i)$:

$$f(r, t - t_i) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma_i^3(t)} \exp\left(-\frac{r^2}{2\sigma_i^2(t)}\right). \quad (15)$$

Thus f diffuses outward with variance $\sigma_i^2(t)$ that increases with t. The normalization factor $(2\pi)^{\frac{3}{2}}\sigma_i^3(t)$ guarantees that the mass of the blob is invariant under diffusion. Once the variance of a blob becomes comparable to the smallest scale of the turbulent wind field we can replace it by smaller blobs and distribute the mass equally among them. The effect of the dissipation term is an exponential decay of the masses over time:

$$m_i(t) = m_0 \exp\left(-\alpha(t - t_i)\right). \quad (16)$$

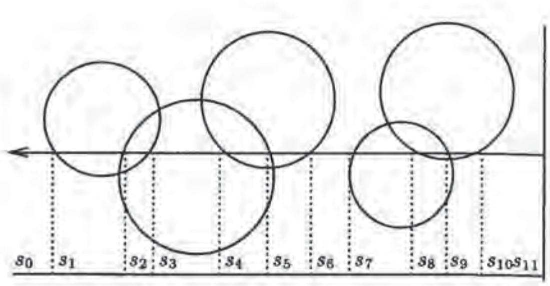

Figure 2: Subdivision of ray into intervals

5 Efficient Rendering of Gas

In conventional ray-tracing, light-object interactions are only computed at object boundaries. Hence light travelling along a ray is only modified at its endpoints. In the presence of a participating medium, the light carried by a ray can be attenuated and increased: attenuation is caused by light absorbed and scattered away by the gas; an increase may arise from light scattered in the direction of the ray from other directions and by self-emission of the gas. These effects can be included into a standard ray-tracer, by modifying the intensity value returned along any ray in the ray-tree. For each such ray we first determine which blobs have domains intersecting the ray (in practice we truncate the domain of each gaussian). For each such blob we store in a sorted list the parameter value s both for the entry and exit points of the ray. This subdivides the ray into N disjoint intervals $I_i = [s_i, s_{i+1}]$ $(i = 0, \cdots, N-1)$ as illustrated in Figure 2, with $s_0 = 0$ being the origin of the ray and the s_i being points of ray/blob intersections.

Once the ordered list of blobs intersecting the ray is calculated, the intensity of light C reaching the origin of the ray is computed by shading the list from front to back [6]:

```
τ_total = 1
C = 0
for i = 1 to N − 2 do
    C = C + τ_total(1 − τ_i)C_i
    τ_total = τ_total τ_i
end for
C = C + τ_total C_N,
```

Here, τ_i is the transparency of the density distribution on interval I_i, and C_i is the intensity of light emitted on that interval by the density distribution. These values are defined in Appendix B, in which we also derive the illumination model. C_N is the intensity returned by the standard ray-tracer. In case the ray is cast to determine a shadow, only τ_{total} has to be returned.

The transparency along an interval I_i due to a single blob is a function only of the distance of the ray to the centre of the blob and the endpoints s_i and s_{i+1} of the interval as shown in Figure 3. The exact relationship and an efficient way to compute them is given in Appendix B. The transparency τ_i of the interval is then computed by

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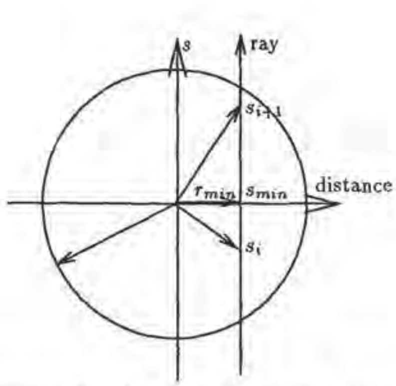

Figure 3: Calculation of transparencies τ_i

combining the transparency values calculated for each blob that intersects the ray along that interval.

Instead of testing separately for an intersection of the ray with each blob, we traverse a tree data structure of bounding spheres. The tree is constructed prior to rendering a frame as follows. First all the blobs are put in a linked list. The tree is then constructed by the following algorithm:

```
while list has at least two elements do
    for each blob b in the list do
        search for blob b' closest to b
        remove b' from list
        create new blob b'' which bounds b and b'
        set b and b' to children of b''
        replace b by b'' in list
    end for
end while
```

There are some obvious optimizations that can be made to this brute-force algorithm, such as non-binary blob groupings and the use of a k-d tree to accelerate the search, but the cost of ray tracing overwhelms even brute-force preprocessing cost. On average, the use of the tree data structure has reduced rendering times by an order of magnitude. The tree can be thought of as a multi-scale representation of the density distribution and hence could be used to render the distribution at different levels of detail.

6 Interactive Field Modelling/Results

In our implementation, modelling wind fields and their effects consists of several steps. First the energy spectrum for the spatial component of the small-scale turbulence is specified by providing numerical values for the rate ϵ and the inertial frequency k_{inertial} of the Kolmogorov energy cascade. The standard deviation σ for the temporal component of the energy spectrum is also specified. The overall energy spectrum (cf. Section 3.2) is the product of the temporal and spatial (Kolmogorov) energy spectra. A 4-D vector field is then generated (cf. Section 3.3) which can be placed in a library (although its computation is swift).

We have developed an interactive animation system in which an animator can design a complex wind field and visualize its effect on a gas density. Complex wind fields are formed by the superposition of small-scale turbulence with large-scale fields such as directional, spherical, and exponentially decaying fields. The user is also able to change the grid spacing of the small scale independently in each component of space and time, allowing the specification of non-homogeneous fields. This also permits the same prototypical small-scale field to be given different behaviours in different contexts (which is precisely what has been for the images shown below).

Our animation system also simulates the effect of a wind field on a gas. A specific gaseous phenomenon is specified as a particle system characterized by the following values: the region over which blobs of particles are born, their birth rate, and the initial standard deviation and the initial mass of each blob. During a simulation, the system introduces blobs at the given rate, animates their motion by advection, modifies the standard deviations by diffusion and the masses by dissipation, as described in Section 4. Additionally, particles can be given illumination parameters such as a colour. In this modelling step the centre of each blob is depicted (with intensity modulated by parameters such as duration), but positions and other data can be piped into a high-quality renderer for image synthesis. About 6,000 particles can be animated in real time on an SGI Indigo.

The parameters needed for rendering include (Appendix B): the extinction coefficient κ_t, which describes the decay of light in inverse proportion to distance; the albedo $\Omega \in [0,1]$, which defines the proportion of light scattered at a given point; the phase function p, giving the spherical distribution of scattered light; and self-emission Q, which is the amount of light emitted by a blob at a given position. The illumination computation for gas densities at a resolution of 640×480 typically requires from one to ten minutes, although 1-2 hour computations are possible when rendering scenes of high optical complexity.

For the images presented below, we have assumed that the phase function is constant and we have ignored shadows cast onto the density distribution for all but one image sequence. In all simulations the same statistical parameters were used for the small scale component: $\epsilon = 1$, $k_{\text{inertial}} = 4$ and $\sigma = 1$.

Steam from a mug: One global directional wind field was used to model the rising of the steam due to thermals. The particles were generated uniformly on a disk.

Psychedelic steam: Three trails of smoke of different colours were combined. As for the steam we used a directional wind field, this time tilted in the direction of the teapot spout. Particles were again generated on small disks.

Cigarette smoke: Two smoke trails originating from the tip of a cigarette are derived from the similar small-scale turbulence as the steam with a directional heat source.

Interaction of a sphere with smoke: This simulation shows how objects can interact with our wind field model. Instead of testing for collision of particles with the objects, we define a repulsion field around each object. We modelled the repulsion force by a radial potential field. The sphere is moved along a path given by a spline curve. Note that this image sequence depicts self-shadowing.

Three-dimensional morphing: The cylindrical range data of two human heads was converted into two sets of blobs and input to the animation system. The scene was illuminated by setting the self-illumination parameter (Q in Eq. 24) of each blob to the illumination given by the range data. The albedo was set to zero and dissipation was set to a large value to allow rapid dissolution of each set of blobs (with one run in reverse).

7 Conclusions and Extensions

We have presented a new model for the visual simulation of gaseous phenomena in turbulent wind fields. Our model provides an animator with control over both the large-scale motion and the statistical features of the small-scale turbulence. This model has been successfully applied to the animation of gaseous phenomena. Our model, however, can be applied to many other phenomena resulting from the interactions of objects with a wind field. For example, the wind field model can be included in any existing physically-based animation system. Our model can in fact generate a random vector field of any dimension, not only three-dimensional vector fields with a four dimensional domain. The derivation of the algorithm can be adapted in a straightforward manner. Our fast rendering algorithm can be used to visualize sparsely sampled data. The rendering of the heads in the morphing animation is a good example. Also our animation system could be used to visualize wind fields calculated by direct numerical simulation for fluid dynamics applications.

There are many other extensions to our model that we will explore in future research. We have assumed that the large scale motions of the wind do not modify the small turbulent scale. This is implausible. One possible solution is to warp the domain of the turbulent scale according to the large scales. We would require the use of a global deformation algorithm. Also it is possible to use a physical model for the large scales. A numerical technique in computational fluid dynamics known as *Large Eddie Simulation (LES)* solves the Navier-Stokes equations on a coarse grid using a statistical model for the small scales [11]. However, a physical simulation might not be relevant in computer graphics when a specific behaviour is intended.

A Inverse FFT Method Derivation

A white noise velocity field has cross-spectral density functions defined by:[3]

$$\Phi^w_{kl}(\mathbf{k},\omega) = \langle \hat{w}^*_k(\mathbf{k},\omega)\hat{w}_l(\mathbf{k},\omega)\rangle = \delta_{kl}. \qquad (17)$$

A random field with cross-spectral density functions Φ_{ij} can be obtained by *cross-convolving* this white noise with a set of deterministic kernels h_{kl}:

$$u_k(\mathbf{x},t) = \sum_{l=1}^{3} \int_{\mathbf{R}^3}\int_{-\infty}^{\infty} h_{kl}(\mathbf{x}-\mathbf{y},t-s)w_l(\mathbf{y},s)\,ds\,d\mathbf{y}, \qquad (18)$$

which in the Fourier domain becomes

$$\hat{u}_k(\mathbf{k},\omega) = \sum_{l=1}^{3} \hat{h}_{kl}(\mathbf{k},\omega)\hat{w}_l(\mathbf{k},\omega). \qquad (19)$$

We obtain an equation for the transformed kernels $\hat{h}_{kl}$ in terms of the cross-spectral density functions Φ_{ij} by inserting the expressions for the Fourier velocity components $\hat{u}_i$ and $\hat{u}_j$ given by Eq. 19 into the definition of the cross-spectral density function Φ_{ij} (see Eq. 6).

$$\begin{aligned}\Phi_{ij}(\mathbf{k},\omega) &= \langle \hat{u}^*_i(\mathbf{k},\omega)\hat{u}_j(\mathbf{k},\omega)\rangle \\ &= \sum_{k=1}^{3}\sum_{l=1}^{3} \hat{h}^*_{ik}(\mathbf{k},\omega)\hat{h}_{jk}(\mathbf{k},\omega)\Phi^w_{kl}(\mathbf{k},\omega) \\ &= \sum_{n=1}^{3} \hat{h}^*_{in}(\mathbf{k},\omega)\hat{h}_{jn}(\mathbf{k},\omega). \qquad (20)\end{aligned}$$

We thus have 9 equations for the 9 kernels $\hat{h}_{kl}$ in terms of the cross-spectral density functions. Because of the symmetry of the cross-spectral density functions ($\Phi_{ij} = \Phi_{ji}$), only 6 of these kernels are independent and three kernels can be chosen arbitrarily. If we set $\hat{h}_{12} = \hat{h}_{13} = \hat{h}_{23} = 0$, then the system of equations given by Eq. 20 becomes diagonal and can easily be solved as follows.

$$\begin{aligned}\hat{h}_{11} &= \sqrt{\Phi_{11}}, \quad \hat{h}_{21} = \frac{\Phi_{21}}{\hat{h}_{11}}, \quad \hat{h}_{31} = \frac{\Phi_{31}}{\hat{h}_{11}} \\ \hat{h}_{22} &= \sqrt{\Phi_{22} - \hat{h}^2_{21}}, \quad \hat{h}_{32} = \frac{\Phi_{32} - \hat{h}_{31}\hat{h}_{21}}{\hat{h}_{22}} \\ \hat{h}_{33} &= \sqrt{\Phi_{33} - \hat{h}^2_{31} - \hat{h}^2_{32}}. \qquad (21)\end{aligned}$$

B Illumination Model

Consider a ray $\mathbf{x}_s = O + sD$, with origin O and direction D. Let C_N be the intensity of light reaching O along the ray from point $\mathbf{x}_b$ in the absence of a density distribution (i.e., given by a conventional ray-tracer). If we ignore multiple scattering effects, then the illumination C_0 reaching point O along the ray for each visible wavelength λ is [3]

$$C^\lambda_0 = \int_0^b \tau^\lambda(0,s)\rho(\mathbf{x}_s)\kappa^\lambda_t C^\lambda(\mathbf{x}_s)\,ds, \qquad (22)$$

where

$$\tau^\lambda(s',s'') = \exp\left(-\kappa^\lambda_t \int_{s'}^{s''} \rho(\mathbf{x}_s)\,ds\right), \qquad (23)$$

$$C^\lambda(\mathbf{x}_s) = \Omega^\lambda L^\lambda(\mathbf{x}_s) + (1-\Omega^\lambda)Q^\lambda(\mathbf{x}_s), \qquad (24)$$

and κ_t is the *extinction coefficient*, and Ω is the *albedo*. The term $L(\mathbf{x}_s)$ is the contribution due to N_l light sources:

$$L^\lambda(\mathbf{x}_s) = \sum_{k=1}^{N_l} p^\lambda(cos\theta_k(\mathbf{x}_s))S_k(\mathbf{x}_s)L^\lambda_k, \qquad (25)$$

where p is the phase function characterizing the scattering properties of the density distribution, the θ_k are the angles between the ray and the vectors pointing to the light sources, S_k determines if the light source is in shadow and L_k is the colour of the light source. The term $Q^\lambda(\mathbf{x}_s)$ accounts for self-emission and can be used to approximate the effects of multiple scattering. If we assume that $C^\lambda(\mathbf{x}_s) = C^\lambda_i$ is constant on each interval I_i, which is reasonable in the case of many small blobs, then Eq. 22 becomes

$$\begin{aligned}C^\lambda_0 &= \sum_{i=0}^{N-1} C^\lambda_i \int_{s_i}^{s_{i+1}} \tau^\lambda(0,s)\rho(\mathbf{x}_s)\kappa^\lambda_t\,ds \\ &= \sum_{i=0}^{N-1} C^\lambda_i \left(\tau^\lambda(0,s_i) - \tau^\lambda(0,s_{i+1})\right). \qquad (26)\end{aligned}$$

If we define $\tau^\lambda_i = \tau^\lambda(s_i, s_{i+1})$ as the transparency along interval I_i then the equation becomes

$$C^\lambda_0 = \sum_{i=0}^{N-1}\left(\prod_{j=0}^{i-1}\tau^\lambda_j\right) C^\lambda_i \left(1-\tau^\lambda_i\right). \qquad (27)$$

We now show how the integral occurring in the calculations of the transparencies τ^λ_i can be computed efficiently. Let us assume that the blobs $\rho_{j_1},\cdots,\rho_{j_{n_i}}$ intersect the ray on interval I_i. The transparency on interval I_i is then

$$\tau^\lambda_i = \exp\left(-\kappa^\lambda_t \sum_{k=1}^{n_i}\int_{s_i}^{s_{i+1}} \rho_{j_k}(\mathbf{x}_s)\,ds\right). \qquad (28)$$

[3] All subscripted indices in this appendix take on the values 1, 2, 3.

As we render for a particular frame in time we define $\sigma_j^2 = \sigma_0^2 + \kappa(t-t_j)$ and $m_j = m_j(t)$. Using these definitions, each integral in Eq. 28 can be written as [8]:

$$\int_{s_i}^{s_{i+1}} \rho_j(\mathbf{x}_s)\,ds = \frac{m_j}{(2\pi)^{\frac{3}{2}}\sigma_j^3}\int_{s_i}^{s_{i+1}} \exp\left(-\frac{r_{min}^2+(s-s_{min})^2}{2\sigma_j^2}\right) ds$$

$$= \frac{m_j}{(2\pi)^{\frac{3}{2}}\sigma_j^2}\exp\left(-\frac{r_{min}^2}{2\sigma_j^2}\right)\left(T\left(\frac{s_{i+1}-s_{min}}{\sigma_j}\right)-T\left(\frac{s_i-s_{min}}{\sigma_j}\right)\right).$$

The first equality results from the geometry of Figure 3. The function T is the following integral:

$$T(s) = \int_0^s \exp\left(-\frac{u^2}{2}\right) du, \qquad (29)$$

and can be precomputed and stored in a table for efficiency.

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Sphere interacting with a gas (note the shadowing)

375

A strange brew

The lonely cigarette

From David to Heidi

Real Virtuality: StereoLithography — Rapid Prototyping in 3-D

Chair:
Jack Bresenham, Winthrop University

Panelists:
Paul Jacobs, 3D Systems Inc.
Lewis Sadler, University of Illinois at Chicago
Peter Stucki, University of Zurich

Realistic Virtuality
Solid reality from virtual abstractions is now possible in mere minutes. Innovations in laser generation of 3-D objects offer rapid prototyping from computer synthesized graphics or scanned images to real solids in just a few hours or less. Photopolymers and thermoplastics offer new expectations for CAD, visualization, manufacturing, and medicine. Panelists from industry and academe will discuss current state-of-the art and expectations for the future of instant 3-D copies using new technologies such as StereoLithography, laser sintering, and fused deposition.

Panel Background
Real virtuality, in contrast to virtual reality, takes abstract images from computer synthesis and quickly turns them into actual 3-D objects as reality. This 'glimpse ahead' panel addresses use of StereoLithography, laser sintering and fused deposition as techniques for rapid prototyping. Engineering, manufacturing, medical, and artistic uses of this new technology offer significant growth potential as we enter the 21st century.

This panel brings together three leaders in innovative use and leading edge research for stereolithographic rapid prototyping. All of the panelists have been active in this new field of instant prototyping using laser-induced polymerization of photocurable resins. They will discuss industrial applications, biomedical usages, university research, associated software, and their views of what future challenges are likely in this rapidly developing technology.

Panel Goals and Issues
A glimpse ahead is the objective of this panel. Laser generated 3-D embodiments of virtual objects synthesized in CAD can be created as real physical objects in not much more time than was taken for 2-D computer plots a couple of decades ago. Panelists will discuss successful commercial applications and on-going research in which they're involved. They'll also address anticipated areas of activity such as data exchange standards, chemical & mechanical properties expectations, productivity enhancement and software paradigms.

The panel will first present views of 'real virtuality' or rapid prototyping together with illustrations of their work. To conclude the session they'll answer questions from attendees. If you've never seen laser generated 3-D parts nor held a computer fabricated polymer knee joint or gear box, the panelists will introduce you to this rapid prototyping in 3-D. If you're already quite knowledgeable and working in the area, the panel will share their research areas with you and expect you to comment and to question and to share your experiences of your own research and applications of StereoLithography.

Paul Jacobs
Currently over 370 StereoLithography Systems have been installed at major corporations, universities, government agencies and service bureaus in 25 countries on five continents. Dramatic cost and time savings have been achieved through the ability to rapidly proceed from the idea for an object to the object itself. The ability to hold a real object in your hands, to look at it from different directions, and to take advantage of the human brain's extraordinary pattern recognition capability has been one of the earliest benefits of this exciting new technology. We have referred to these capabilities for the early detection of design errors under the general headings of Visualization and Verification. The great majority of Rapid Prototyping and Manufacturing (RP&M) systems in current use have been justified on the basis of improved design visualization and verification.

However, during the past year we at 3D Systems have become aware of numerous applications of StereoLithography for design Iteration and Optimization. Substantial improvements in part accuracy, comparable to CNC machining, coupled with the proven ability to generate such objects very rapidly, at low cost and with greatly improved reliability, has now made it possible for designers and engineers to produce three, four or even five interactions within a few weeks. The result: improved product designs with fewer errors, available quickly, at lower cost.

Finally, we are now moving into an incredibly exciting era in which RP&M will enable the designer or engineer to achieve prototype and or limited run manufacturing Fabrication in final, end use, materials. With the release of the new QuickCast™ build style by 3D Systems, numerous users have already generated CAD models of a wide range of objects of varying complexity, produced a QuickCast quasi-hollow pattern of the object, and then, working directly with specific foundries, received precision shell investment castings of these objects in aluminum, stainless steel, beryllium cooper, titanium, silicon bronze, and incomel. The ability to generate functional prototypes, without the need for tooling, can save many months and tens to hundreds of thousands of dollars per component. Aggressively pursued, RP&M has the potential to significantly enhance industrial productivity.

Lewis Sadler
Rapid prototyping technology offers many advantages to biomedical applications that were previously unavailable. The ability to model complex, compound geometries is essential in the fabrication of maxillofacial prosthetics, facial implants, selected somato prostheses as well as anatomical models and simulators that have been developed to assist in surgical planning. Clinical experience has proven the efficacy of rapid prototyping technology as a new tool in the armamentarium of the surgeon in the restoration of facial cosmesis. The unusual educational mix of communication media (all of which are becoming digital) and the basic biological sciences (anatomy, pathology, physiology, histology, embryology, and genetics) and over twenty years of practical experience in communication problems for researchers and basic scientists have provided me with the necessary background to serve as liaison between groups of biomedical scientists and engineers. My experience is that these two

groups have no common background, no shared language or customs and act very much as separate nations, unable to communicate effectively with each other. BVL's success in this new technology area relates to the establishment of a multidisciplinary team in both the biomedical sciences and in engineering.

Peter Stucki

While a minimal set of algorithms and data structures have evolved for laser generation of 3D copies, further research and experimentation is necessary to achieve a good set of standard formats, algorithms, and tools. Abstract languages, formats for CT, PET and MRI scans, and specialized CAD/CAM software tools for rapid 3D object prototyping with StereoLithography, laser sintering and fused deposition are active research areas. Shrinkage compensation, cross-industry data exchange, and device characterizations are also fruitful areas for future advances. My multi-media laboratory at the University of Zurich has been involved for the past three years in the subject topic and I look forward to sharing our outlook. Of special interest are:

Chemistry for StereoLithography and Rapid Prototyping: The process of photopolymerization, e.g. the process of linking small molecules into larger molecules comprised of many monomer and oligomer units is key and will be shown as animated scientific visualization. For StereoLithography, radical and cationic processes of multifunctional monomers and oligomers resulting in cross linked polymers are of prime interest. Topics for discussion: building properties, mechanical characteristics.

Informatics for StereoLithography and Rapid Prototyping: 3D interactive computer graphics and natural image processing as well as their underlying algorithms, procedures and software tools represent the back-bone for StereoLithography and Rapid Prototyping object reconstruction. A systematic approach to classify processing options available includes the procedures of interactive and automated object design as well as procedures of interactive and automated object analysis. Data exchange standards such as the SLA and SLC formats are key in making StereoLithography and Rapid Prototyping applications platform independent. Yet, data volumes are enormous and very often represent the critical upper bound of what can be handled with ease in a given workstation environment. Topics for discussion: algorithmic efficiency, automatic and semi- automatic procedures, standards, hardware platforms, networks, application programming paradigms.

Post-Processing of StereoLithography and Rapid Prototyping Models: Topics for discussion: silicon casts, epoxy cast, metal cast, quick casting.

StereoLithography and Rapid Prototyping for CIM Applications: Topics for discussion: responding to fast changes, reducing time- to-market, total product modeling, prototyping and test quality control, pre-production marketing.

Jack Bresenham

In the late 1950's and early 1960's, research and use of numerical tool control was a hot 'computer' topic and leading edge graphics application. APT is a cooperative research & joint development effort I recall as having significant impact. Today laser generation of instant, or rapid prototype 3-D objects is a comparable new technology. It can allow blind persons to more easily 'view' mathematical functions, doctors to model individualized joints or restorations, and car manufacturers to model engine blocks without prohibitive cost and time delays that made typical tooling set-up for multiple models impractical. Our panelists each have well established reputations of long standing in other areas of computer graphics, imaging and visualization. For the past several years each has devoted significant research effort to advance the state of the art in laser generation of 3-D objects for rapid prototyping. I believe you'll find their insights into what I sometimes call instant 3-D hardcopy to be truly a glimpse ahead into what Dr. Stucki often calls real virtuality.

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Visual Thinkers in an Age of Computer Visualization: Problems and Possibilities

Chair:
Kenneth R. O'Connell, University of Oregon, Eugene

Panelists:
Vincent Argiro, Vital Images
John Andrew Berton, Jr., Industrial Light & Magic
Craig Hickman, University of Oregon, Eugene
Thomas G. West, Author of *In the Mind's Eye*

We think that the same mind's eye that can justly survey and appraise and prescribe beforehand the values of a truly great picture in one all-embracing regard, in one flash of simultaneous and homogeneous comprehension, would also ... be able to pronounce with sureness upon any other high activity of the human intellect.

—Winston Churchill, *Painting As A Pastime*, 1932

It is now becoming increasingly clear that new technologies and techniques currently being developed in computer graphics, scientific visualization and medical imaging could have important implications in the larger society—in time having a profound effect on education and work at all levels. As visualization hardware and software become more sophisticated and are used more widely, there is a need to focus on differing abilities among individual users. Some are very good at processing visual material, while others find it an area of great difficulty.

For centuries, most of education and many occupations have been largely dominated by verbal approaches to knowledge and understanding. If current trends continue, it seems likely that there will be a gradual but dramatic reversal in many spheres, as powerful visualization techniques are used to find solutions to complex problems that are well beyond the limits of traditional modes of verbal and mathematical analysis. In many fields, visual approaches have been relatively unfashionable and under-used for about a century. Yet visual approaches have been major factors in the most creative and original work of a number of important historical physicists, chemists, mathematicians, inventors, engineers and others.

A dramatic revival of long-neglected visual approaches is already underway in several fields. Mathematicians are rediscovering the power and effectiveness of visual approaches that were long considered unacceptable. Calculus professors, with higher-powered graphic computers and well-designed software, are discovering ways to move rapidly to high level work, even with unexceptional students. Critics of engineering education in recent decades lament the excessive prestige of highly mathematical analysis and design while the "art" and "feel" and high visual content of previous design approaches have been denigrated—leading sometimes to major design failures. The revival of visual approaches is now increasingly apparent at the forefront of many fields. However, the high value of these approaches is nowhere more apparent than in the new fields that have been emerging in the last decade or so—chaos, fractals, system dynamics, complexity.

The continued spread of increasingly powerful and inexpensive graphic hardware and software (together with simulation and interactive media) can be expected to only further accelerate these trends—making it possible for many people to use methods and approaches that previously only a small number of extremely gifted people could apply through their own mental models alone.

Gradually, it is being recognized in some professions (such as engineering, medicine, architecture and scientific research) that those with high visual and spatial talents may have moderate or severe difficulties with certain verbal or numerical material—and that professional training programs that do not (formerly or informally) acknowledge this pattern may serve to eliminate some of the most talented (and ultimately most creative and productive) individuals.

Certain psychologists consider visual-spatial abilities a distinct form of intelligence, like logical or verbal intelligence, while certain neurologists suggest that there may sometimes be an inverse relationship between visual-spatial abilities and conventional verbal and academic abilities. Thus, there is a growing awareness that some very highly gifted visual thinkers may be expected to show a pattern of traits consistent with dyslexia or learning disabilities—having significant difficulties with reading, writing, composition, counting, speaking, memory or attention.

The late Harvard neurologist Norman Geschwind was interested in the apparently paradoxical pattern of high visual talents with verbal difficulties. He observed that "it has become increasingly clear in recent years that dyslexics themselves are frequently endowed with high talents in many areas. ... I need only point out the names of Thomas Edison and Albert Einstein to make it clear that dyslexics do not merely succeed in making a marginal adjustment in some instances, but that they rank high among those who have created the very fabric of our modern world." He suggested "that this is no accident." Rather, "there have been in recent years an increasing number of studies that have pointed out that many dyslexics have superior talents in certain areas of non-verbal skill, such as art, architecture, engineering, and athletics." He argued that the early formation of the brain may explain these patterns and should help us not to be surprised at those who have such mixed abilities.

It is possible, therefore, that conditions are being reversed in a way that will be especially favorable to some strong visual thinkers, many of whom may have had significant difficulties in conventional academic settings. With the further development of these technologies, we may see the development of a new visual language and striking new opportunities for creative, visual thinking persons. Increasingly, we may see them forming bridges between the arts, their traditional stronghold, and the scientific and technical fields that have been closed to many of them. We are used to hearing of scientists, computer programmers and mathematicians who are also talented musicians. Possibly in the future we may see the solution of complex problems in molecular biology, statistics, financial markets, neuroanatomy, materials development and higher mathematics coming from people who are sculptors, graphic artists, craftsmen, film makers and designers of computer graphic visualizations. Different kinds of tools and different kinds of problems may demand different talents and favor different kinds of brains.

As part of the panel, an "overview" presentation will be provided to describe relevant recent neurological and psychological research, to provide brief examples of historical and contemporary visual thinkers and to suggest the possible social, economic, educational and cultural implications of shifting from a predominantly verbal culture to one that is increasingly focused on visual approaches to learning, knowledge and experience. Subsequently, panelists will give presentations referring to their own work in computer graphics—generally representing perspectives related to scientific visualization, education and entertainment. The panelists will discuss and debate the extent to which they agree or disagree with the views put forth by other panelists and issues raised by the audience.

Vincent Argiro

In our need to comprehend space, volume visualization becomes an interdisciplinary adventure. Cells are 3D space-filling objects. Human brains are 3D space-filling objects. The bedrock under the Gulf of Mexico is an enormous 3D space-filling object. In each case we are curious, even desperate to know what lies inside these spaces. We want to see freely inside, with the mere intention to do so, like the Superman of our childhood with his X-ray vision.

We are a long way yet from fully actualizing this vision. But recent strides in digital imaging and computer graphics hardware and software suggest that this goal is becoming less remote. Moreover, in our own adventures with scientists, physicians and engineers, we find striking parallels in the specific visualization, analysis, modeling and communication tools these professionals require. To peer into and comprehend these regions of space, whether microscopic or macroscopic, living or inanimate, common approaches prevail over unique requirements.

This indeed suggests that digital imaging and volume visualization may be creating a fundamentally new visual language for communicating insights into the natural and artificial worlds. My presentation will make this case, illustrated with actual instances of overlap, osmosis and cross-pollination among investigations into cellular, neural, and geologic space.

John Andrew Berton, Jr.

Cinema is a medium where ideas are routinely communicated through primarily visual means. Films and videos are created by strong visual thinkers and viewers' interpretations of these works are based largely on visual information. This is especially true of visual effects work, where images must carry important content with little verbal assistance.

At Industrial Light and Magic, artists and technicians work with film directors and visual effects supervisors to bring important and demanding visual concepts to the screen. The techniques required to achieve these visual effects are often highly technical and, in many cases, based on logical systems, such as computers and computer graphics programs. The results of these techniques are judged in the visual realm, creating a unique opportunity to observe the translation of visual ideas into the verbal/technical realm and back again. Case studies of recent feature film projects at ILM indicate possible solutions to problems faced by visual thinkers in a verbal/technical arena. Topics of discussion include evaluations of how visual thinkers use existing images to describe their vision for images yet to be created and how ILM builds and uses interactive computer graphics tools to help visual thinkers communicate their ideas and create compelling visual effects.

Craig Hickman

While media attention centers on high-end scientific visualization and virtual reality as the epitome of what the computer can offer to visual thinking, a quieter but equally significant revolution is occurring on the desktop. Users are now expecting everyday software to display data in a visually satisfying way, and when they are confused using the software they are less apt to blame their confusion on their own ignorance rather they assume the fault lies with bad software design. The visual logic of software must be as well thought out as the logic of the data structures and software design teams will have greater need for "visual thinkers."

My own software "Kid Pix" attempts to provide a rich visual experience. It approaches this in two ways. First the user interface is as straightforward and as "self defining" as possible. Users are not expected to read a manual to get started and are invited to learn the program by exploration. Second, "Kid Pix" is full of randomness, visual surprises, and visual jokes. Even though these two approaches seem at odds, they support each other.

Thomas G. West

For some 400 or 500 years we have had our schools teaching basically the skills of a Medieval clerk—reading, writing, counting and memorizing texts. But with the deepening influence of computers of all kinds, it now seems that we might be on the verge of a really new era when we will be required to cultivate broadly a very different set of skills—the skills of a Renaissance thinker such as Leonardo da Vinci, recombining the arts and the sciences to create elegant and integrated solutions to urgent and complex problems.

As part of this change, in the not-too-distant future, past ideas of desirable traits could be transformed. In time, machines will be the best clerks. Consequently, in place of the qualities desired in a well-trained clerk, we might, instead, find preferable: a propensity to learn directly through experience (or simulated experience) rather than primarily from books and lectures; a facility with visual content and modes of analysis instead of mainly verbal (or symbolic or numerical) fluency; the more integrated perspective of the global generalist rather than the increasingly narrow specialist; a habit of innovation through making connections among many diverse fields; habit of continuous and life-long learning in many different areas of study (perhaps with occasional but transient specialization); an ability to rapidly progress through many stages of research and development and design using imagination and mental models along with 3D computer-aided design.

Leonardo da Vinci's emphasis on imitating nature and analysis through visualization may come to serve us as well as it served him—providing results well in advance of those who follow other more conventional approaches. Accordingly, in the near future, it seems that we might be in a position to come full circle, using the most sophisticated technologies and techniques to draw on the most elementary approaches and capacities—to simulate reality rather than describe it in words or numbers. To learn, once again, by doing rather than by reading. To learn, once again, by seeing and experimenting rather than by following memorized algorithms. Sometimes the oldest pathways can be the best guides into unfamiliar territory.

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Updating Computer Animation: An Interdisciplinary Approach

Chair:
Jane Veeder, San Francisco State University

Panelists:
Charlie Gunn, Technisches Universitat Berlin
Scott Liedtka, Forensic Technologies International
William Moritz, California Institute of the Arts
Tina Price, Walt Disney Pictures

Computer animation currently enjoys a wide range of applications from children's entertainment to disaster simulation, esoteric mathematics to personal fine art statements. In order to develop useful technology and train future professionals, we need to update our model of "Animation" and "Animator" into a pluralistic model that encompasses these and other applications. This panel will articulate and compare the conceptual framework, design gestalt, relation of design to content, and development process used by the very different animation application areas of entertainment, scientific and engineering visualization, and fine art as well as explore the connection between current forms and historical animation. Lively discussion will highlight points of commonality and contrast, reveal how these fields view each other and what each can learn from the other.

Panel Overview

With the zoetrope and other accessible contraptions, we began the transition from the era of the static media image to that of the dynamic. Motion film and video accelerated this transition and now digital technology is blurring the traditional differences between film and video, the optical and the synthetic image, science and art. For some, "Animation" is synonymous with "Cartoon." For others, it means "Dynamic Simulation.. Do we need new terminology? First, we need updated information: What is the mental model of animation and viewer? How will the needs of the application area drive the development of hardware and software? How does the use of computers impact the design and production process? What are the design constraints? How are design and production roles defined? What backgrounds do these animators have and what new skills must they learn? Who are valuable collaborators? How are "Time," "Space," and "Story" dealt with in each of these application areas? How do these animations relate to historical animation and other forms of contemporary representation? How can technical and media arts education better prepare people to work in these areas?

As animation joins writing as a basic skill for the communication of complex information, we must articulate the combined knowledge and experience of traditional and emerging practitioners. As computer animation, much like computer graphics, becomes a ubiquitous, enhancing technology, we must inform the development of that technology with our design experience and diverse creative goals.

Charlie Gunn

Mathematical animation represents a "return of the repressed": in its best moments, it reaches behind the symbolic artifacts preserved in textbooks to reveal the ding-an-sich of mathematical activity. In this presentation I'll make a case study of the mathematical animation, "Not Knot," tracing the decisions made to convert "equations" into "pixels." I suggest that the conversion is closer to archeology than discovery: behind the equations stands the original human imagination which in many ways is closer to a picture than to an equation. Part of the historical mission of scientific visualization is to reclaim the original form of much scientific creativity, which is intuitive, plastic, dynamic.

Animation is a key ingredient in this revelation by showing the mathematical universe to be alive with metamorphosis and movement. Attempting to open a window onto this universe using standard animation systems is often frustrating. I'll examine how the modeling, animation, and rendering requirements of "Not Knot" could not be met by existing monolithic systems. How can this situation be improved? I propose some guidelines for the design of open and flexible animation systems that have "room to grow" as new directions of mathematical exploration are pursued. Results obtained would have application to wider realms of animation practice. As an example, there are several places in "Not Knot" where transitions to infinity occur. Through integrating such limiting processes into animation technique we can begin to understand and represent qualitative metamorphosis, a key feature of much interesting animation. Such a system would also improve the aesthetic component of mathematical animation by simplifying collaboration with artist/ designers. Going in the other direction, it would also be of interest to artists working in the non-representational animation tradition of Fischinger, Whitney, and Cuba.

Scott Liedtka

At FTI, we produce for the courtroom computer animations that recreate accidents or explain technical processes. In either case, we attempt to teach technical concepts to lay people who must use them to make serious decisions. In doing so, we design our animations to draw attention to important events and to the relationship between different events. We often study an event by changing its timing, speeding it up or slowing it down, using repetition, or even reversing it. Also, our animations are often shown out of order as well because presenters using a bar coded laserdisc have random access to the animation segments we produce. Forensic animation has a special and legal relationship to reality. For instance, most of our motion is based upon recorded real world data, witness testimony, or established dynamics formulas. Camera views may be that of an eye witness or just an unglamorous close-up of a part in the process of failing. Although the technical aspects of our work are significant, it is also important to keep our audience's attention. Traditional animation techniques and timing as well as good design are crucial to keeping our audience watching and learning but we must not cross over into the kind of graphical fictions so successful in the entertainment domain. Our staff, a combination of mechanical engineers with computer artists and media specialists, reflects this balancing act.

Tina Price

In an era of dramatic change and expansion in animation, it is useful to try to define terms and take a new look at convention. I want to look at the long-used design philosophies of full character animation and discuss the difference between character animation and just moving things around. Using the Magic Carpet in "Aladdin" as an example, I'll show and discuss why character animation is so tied to human input and why character animation techniques are effective whether you're using a pencil, a potato or a computer. Just as the application of computers to character animation is changing the complexion of our development process so is "Computer Animation" being transformed by the application of character animation. In order to articulate our current situation, it is useful to identify some aesthetic parallels between the growth and development of early, hand-drawn animation and early computer animation.

Contemporary character animation filmmaking integrates images generated by a variety of techniques and technologies including hand drawn work. Using examples from Walt Disney's Feature Animation Department of computer animation elements from 1986-1993 I will discuss how computers have fit into our traditional animation work flow and, in turn, how they have changed how we view, develop, and produce animation. Some animation work roles have changed dramatically with the introduction of computers, with several traditionally separate roles collapsed into the single role of "Computer Animator."

Computer animation products have recently begun to actively integrate character animation principles and techniques. What direction can animation hardware and software take to support character animation more fully? And how can character animation training change to adjust to the expanding role of computers?

Jane Veeder

Education Fine Arts Animation: Like many others, I moved without benefit or burden of traditional animation training into computer animation as an extension of analog dynamic media (e.g. video, video synthesis) as small digital computers with graphics capabilities appeared in the late 1970's, offshoots of the booming videogame industry. As a fine artist, I have a central interest in digital technology as an inherently dynamic art medium [italics], not merely one of many animation "tools." In addition, much art theory surrounding the fine artist derives from the impact of computers and telecommunications on human culture. Thus I would work with other computer-based media before I would work with non-electronic animation techniques. In the same vein, I appropriate into my work formal conventions and modes of representation from other areas of computer graphics/animation. My design and development process is an interactive, evolutionary one whose open endedness reflects the nature of the medium. Through this method I decided what to do in large part, no simply to do what I have decided. This self-consciousness about the process of interacting with the medium and incorporating that, formally and conceptually, into the artwork is a habit of fine artists. This motivates us to try to interpret the medium to contemporary culture rather than retell old stories in a cost effective or more visually compelling manner.

Animation Education: In all areas of contemporary life boundaries between disciplines are eroding, driven primarily by technological opportunity. Common digital workspaces are arising between the traditional arts disciplines and between the arts and sciences. Fine arts or independent animation may seem a tiny island in a sea of commercial production and engineering/scientific visualization but it is here that most future computer animators are being trained. Soon, animation education everywhere will entail training in both physical and digital media and a merging of vocabularies, techniques, and wisdom. Even more computer and physical science majors will take our courses and more art students will get computer science degree minors. Inspired by the example of a few, early interdisciplinary graduate programs and incorporating new opportunities such as multimedia and virtual reality, we can articulate a new curriculum that embraces a wide range of creative and vocational potential and encourages students to prototype interdisciplinary collaborations.

William Moritz

Since computers are merely tools, "Computer Animation" is not separate from animation produced by other means, so it must be evaluated comparatively. The pin-screen of Claire Parker and Alexander Alexeieff contained 500,000 articulate light-points — quite like pixels — and their 1933 "Night on Bald Mountain" uses them for astonishing transformations of human forms; similarly PDI's morphing for Michael Jackson's "Black or White" video makes brilliant use of transformations to reinforce a social message, while the banal use of morphing in ads for soda pop and autos seems futile. John Lasseter's "Luxo, Jr." is an excellent character animation, even using the limitations of his programs (the rather glossy plastic/metallic surfaces) as part of the characters. Larry Cuba's "TWO SPACE" is an outstanding abstract animation, with a conceptual framework of positive and negative space that gives it a metaphysical resonance: inclusion/exclusion, matter/anti-matter, being and nothingness and creation out of nothingness. "Not Knot" is fine scientific educational animation in that it teaches not only spatial geometry but also our perceptual experience of it and how we learn about our world through seeing.

Summary

Animation is a field whose knowledge base and diversity of application is expanding rapidly. In order to develop useful tools and train successful students, we need to know more about how various application areas are using animation, how animation is impacting the applications, and what new problems, concepts, and opportunities for creativity are emerging. With this panel, we do not hope to close the discussion with definitive answers to all attendant questions, but rather to open it wide.

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Facilitating Learning with Computer Graphics and Multimedia

Chair
G. Scott Owen, Georgia State University

Panelists
Robert V. Blystone, Trinity University
Valerie A. Miller, Georgia State University
Barbara Mones-Hattal, George Mason University
Jacki Morie, University of Central Florida

Abstract
With the recent advent of inexpensive yet powerful computers, the use of high quality graphics and multimedia systems to facilitate learning is rapidly increasing. This panel will review leading-edge work by focusing on several areas, including computer science, mathematics, biology, and art and design. Each panelist will describe how they currently use computer graphics and/or multimedia and give their view of future applications. Emphasis will be placed on how using these techniques fosters interdisciplinary collaboration both for creating learning environments and for working in these career areas.

Panel Overview
It is becoming increasingly evident that a highly educated and/or skilled work force is necessary for a successful economy, thus the need for more effective means of education/training is extremely important. Recent developments in technology have created the possibility of a paradigm shift in the delivery of information. Such a paradigm shift requires a change in the way we define and understand information exchange, resulting in more effective means of communication. One way in which this change may be effected provides for the possibility of interaction and integration of traditional disciplines to maximize the potential of these emerging technologies.

The objective of this panel is to investigate how this paradigm shift is being implemented in several areas of learning. While the focus is on academic areas of learning, the lessons learned and principles developed will also apply to industrial training and continuing education.

Robert V. Blystone: Computer Graphics in Undergraduate Biology
Biological microscopy is a visual discipline; however, when traditionally used in support of undergraduate learning, microscopy is descriptive, of limited sample size, and two dimensional. By coupling computer graphics with biological microscopy, these limitations can be overcome. At Trinity University, microscope intensive courses such as histology and embryology have been dramatically enhanced through this union of computer graphics and microscopy.

The application of graphics can expand two dimensional microscope images into three and four dimensional data sets. Two approaches have been commonly employed in our lab to develop digital scientific visualizations. The first approach utilizes images of intact structures such as embryos or blood cells. These images are collected under conditions of different age or treatment and then morphed to create visualizations of change through time. As an example, the white blood cell known as a neutrophil demonstrates significant changes in its nuclear shape during its week long existence in the circulation. By collecting images of different aged neutrophils and then morphing these images, a "virtual" time lapse movie can be created to represent the aging process. The second approach requires the image capture of sequential (serial) images (sections) of histological elements. These serial sections can be digitally "glued" back together and projected into three dimensional space. Projections taken at different times can be morphed to show change in three dimensions. As an example, projected serial sections through the developing pituitary of a chick embryo of one age can be morphed with a different aged embryo and, as a consequence, the pituitary can be made to grow in space through time. Animations of these types allow for discussions and inquiry-based activities never before possible in the lab and well as the lecture.

Biology students are generally unskilled in the use of computer graphics; thus, lab exercises had to be carefully organized to lead the students into the transparent use of computer graphics so as not to take time away from the biology subject material. As students request to do undergraduate research utilizing this technology, they must agree to tutor students new to the technology. Further, as students developed quality animations and image analysis procedures, the results could be saved and incorporated into the next semester's class.

Valerie A. Miller: Computer Graphics in Undergraduate Mathematics
The use of graphical images has been traditional in teaching lower level mathematics. However, when a student enters a mathematics class beyond the calculus level the use of images disappears, except for the occasional graph theorist's graph or the plotting of a function. This is rapidly changing, as the use of computer graphics and multimedia in teaching and learning mathematics is a mode of instruction that is becoming an accepted technique in the classroom. With the advent of inexpensive graphing calculators and various software packages that assist in the visualization of 2- and 3-dimensional mathematical concepts, mathematics instruction is beginning to examine avenues of learning other than endless rote calculations.

As an example of mathematical visualization in numerical analysis, we present ways in which this may be used to aid the instruction of iterative techniques for solving the problem $f(x) = 0$. Fractal images are generated based upon the number of iterations needed for convergence for various functions via various methods. These images are then presented simultaneously so that the important aspects of each of these methods, such as the order of convergence and cost per iteration, can be more easily illustrated, compared and, hence, more thoroughly understood. The concept of one method being "more expensive" than another is one that is not easily understood by students and the ability to inspect these "costs" visually is very appealing.

Fractal images that are generated based upon the basins of attraction of a function are also presented as means of illustrating how an iterative method can converge to an unwanted solution. As there are many possible criteria for terminating an iterative process, two different criteria are used to illustrate the subtle effects of a stopping criterion to the student.

Barbara Mones-Hattal: Using Computer Graphics to Teach Art Concepts

Currently, in the art and design area, computer graphics and computer imaging are taught as separate course of study in many schools. At these schools, software tools are used primarily to investigate potential computer applications in 2D and 3D design, animation, and interactive design. The available software tools are designed for the artist to create end-products such as illustrations, design for print, and all forms of animation. To a degree, tool and medium aspects of the technology are very difficult to isolate. However, using these same tools, one can de-emphasize the end-product and more fully explore the design process. It is this process of exploration that underscores the potential of computer graphics and multimedia for facilitated learning.

In this panel session, an overview of projects in the fine and applied arts, from intermediate to advanced level, will be presented. These projects focus on the enhancement of the learning process by utilizing computer graphics or multimedia tools (including paint and draw software, modeling and animation software, stereo display, and virtual reality tools). In some cases, mixing computer skills with other real world objects is included. The acquisition of computer graphics skills is less important in these cases as the purpose is to learn to communicate sensory information effectively and expressively. Important questions involving the potential to use the technologies to pose questions to the participant/viewer about the relationship of physical realities to simulate realities will be discussed.

Computer Graphics and multimedia options have provided many profoundly more efficient ways to learn about basic concepts such as color theories and applications, spatial relationships, and mixed media design. Some new additions to the repertoire of tools available are emerging as the inter-relationship of dimensional design forces us to separate our tools into paint (2D), modeling (3D), or moving images (4D), and encourages us to think of developing our works in new and innovative ways.

Learning both fundamental and sophisticated skills is important as both are required of the artist/designer. But some combination of these skills will enhance the capabilities of the non-artists, or any participant in a collaborative or interdisciplinary research team who wishes to work with artists. As more and more computer graphics and multimedia professionals seek to integrate their skills in order to develop and deliver better products, more effective ways to create and enhance learning environments are needed.

Jacquelyn Ford Morie: Using Computer Graphics to Teach Computer Graphics Concepts to Art Students

It is well known that students learn most effectively with hands on experience that reinforces concepts presented by an instructor through assigned reading or lectures. In computer graphics students can read extensively about a particular technique or algorithm, and still not fully understand it. Providing students with hands on exercises can cause an immediate and intuitive understanding of a complex graphic concept.

Computer Science students studying computer graphics have long been expected to have a "hands on" understanding of graphics algorithms in the context of writing the code to implement them. While this does provide a very thorough and complete understanding of the mechanics of how a given procedure works internally, the overhead of writing code is not the only method to cultivate understanding of graphics concepts. In addition, it may not be the most effective way for a student to understand the rich possibilities inherent in a given graphics technique. For example, writing an L-systems piece of code, while challenging, does little to uncover the wealth and variety of forms it is possible to make with such a system. An interactive program that allows a student to play with making many fern-like objects through L-system rules can, in an hour's time, provide a different and valuable intuitive grasp of the concepts behind the process.

This type of learning is also accessible to a greater range of students. This is especially true for visually oriented students, such as the computer animation students (in both art and film programs) that I have been teaching for the last five years. It is sometimes difficult to get them to read research articles or popular magazine articles about various computer graphics techniques. Give these same students an interactive demo on a computer and it is difficult to get them to go home.

Many such programs are available commercially or through public domain sources. Silicon Graphics provides a series of "Button Fly" demos which illustrate some concepts such as B-splines, environment mapping, ray tracing, and radiosity. There are many interactive fractal generating programs on the market. In conjunction with videos, such as those available from computer graphics suppliers, such as the SIGGRAPH Video Review, these can be valuable tools for understanding. In addition, advanced computer science students can provide interactive instructional programs and tools in the context of a summer class or independent study. These can then be tested and used by students of all disciplines studying computer graphics concepts.

Some very interesting results of using computer graphics to teach Computer Graphics concepts include the following:

- Visually-oriented students get "hooked." Since many of these same students are very "process-oriented" (e.g. they have a keen interest in following through a project from mechanics to the final creation), they become very curious about the process behind computer graphics. Some even enroll in UNIX and computer programming classes. If it is seen to be a means to their specific ends, they will spend the effort to become knowledgeable about all aspect of the process.
- Computer Science students see a greater picture and spend the extra time and effort to make their demo or program "better" than the interactive demo they have been exposed to, increasing the amount of learning they derive from the exercise.

G. Scott Owen: Computer Graphics and Multimedia in Computer Science

While computer graphics has been somewhat used to teach computer graphics, it has not been much used in the rest of the computer science curriculum. This is beginning to change as more instructors are beginning to develop and use graphics software to illustrate different concepts. Graphics programs are used in courses to illustrate such concepts as graphs or tree structures. Algorithm animation has been used at a few select places on workstations but is now becoming available on PC-class machines. Another use of graphics is in programming assignments for introductory classes. Multimedia has just begun to be used and I will discuss one system, HyperGraph, which is used to teach computer graphics. HyperGraph runs on PCs and consists of text, images, animations, and video. HyperGraph is being developed by both artists and computer scientists and the ultimate goal is for it to be used by both types of students for learning aspects of computer graphics.

Panel Summary

The examples given in this panel session of using computer graphics and multimedia for learning should help others who are thinking of incorporating these techniques into their own teaching. Lessons learned can also be incorporated into industrial training systems.

Visualizing Environmental Data Sets

Chair
Theresa Marie Rhyne, Martin Marietta/U.S. EPA Scientific Visualization Center

Panelists:
Kevin J. Hussey, Jet Propulsion Laboratory
Jim McLeod, San Diego Supercomputing Center
Brian Orland, University of Illinois/Landscape Arch.
Mike Stephens, Computer Sciences Corp./U.S. Army Corp of Engineers
Lloyd A. Treinish, IBM T. J. Watson Research Center

This panel session focuses on issues pertaining to visualizing environmental sciences data sets. Here the term "multi-dimensional" refers to the simultaneous display of data sets associated with air quality, water quality and subsurface contaminated soil regions. Issues associated with facilitating collaborative environmental visualization efforts among various research centers are presented. These include high speed networking, data base management, visualization toolkits, and heterogeneous computing platform concerns.

Visualization researchers dealing with the display of environmental sciences data sets present their different viewpoints on controversial issues. Panelists highlight and contrast projects associated with the U.S. Environmental Protection Agency, the U.S. Forestry Service, the Jet Propulsion Laboratory, Scripps Institute of Oceanography, National Aeronautics and Space Administration, U.S. Army Corps of Engineers, IBM T.J. Watson Research Center, University of Illinois, and other government, university, and industry centers working with environmental data sets.

The controversial issues include:

- Visualization of Multi Model data: issues associated with validity of data and approaches to data consolidation for a single visualization are discussed.
- Toolkit Applicability: Each panelists has their own unique viewpoint on how and when toolkits should be used for environmental research projects.
- Renaissance Teams (yes or no??): Some of panelists are at visualization centers which continue to advocate collaborative efforts among researchers, programmers, and artists for environmental visualization projects. Other panelists are involved with efforts focused on developing tools for the direct use by environmental researchers with minimal involvement of Renaissance Teams.
- Research versus Policy Making: Visualization for research efforts versus visualization for regulatory and policy making efforts can yield different end products and toolkit requirements.
- Data Format Standards: Multi dimensional environmental visualization involves the merger of data from multiple sources. This points toward the controversial issue of whether a standard data format for environmental research models which supports heterogeneous computing should be required.
- Data Management: The management of terabyte and gigabyte data sets is one of the critical challenges to environmental research and visualization.

Multi-dimensional data visualizations not only require management of data from satellites but also the maintenance of historical geological data sets.

Theresa Marie Rhyne

The U.S. EPA Scientific Visualization Center serves the U.S. Environmental Protection Agency's community of researchers throughout the United States and collaborates on interagency and university research projects. Within EPA, there are a wide range of interests. The Visualization Center has depicted pollutant transport and deposition in regional domains of the United States, total global ozone distribution, fluid flow around buildings, sedimentation in large bodies of water, subsurface contaminated soil regions, and the molecular chemistry of carcinogens.

Visualization toolkits are used by researchers to examine their data, and intensive 3-day workshop sessions are designed to handle environmental researchers' desires for training in the use of these toolkits. High speed networking concerns and the development of visualization tools to support heterogeneous computing platforms across the Agency are explored using the U.S. EPA's National Environmental Supercomputing Center, located in Bay City, Michigan. Collaborations on multi-dimensional environmental visualizations that display the co-registration of air quality, water quality, and subsurface soil data sets are underway. Issues associated with visualization technology transfer to State and local government environmental protection agencies are being examined.

Jim McLeod

Faced with ever increasing environmental data collection rates (soon approaching terabytes of information a day), the ability to disseminate and analyze these data sets at comparable rates is crucial to the success of future global studies. Visualization plays a vital role. However, visualization should not overshadow the ultimate goal of scientific discovery and global understanding. To this end, visualization should hold equal weight with traditional scientific analysis techniques until its value as a research tool can be measured and evaluated. At the Advanced Scientific Visualization Laboratory in the San Diego Supercomputer Center, we provide a multi-level visualization support service. By utilizing visualization toolkits, at one level, to obtain analytical imagery quickly, researchers and members of our visualization staff (collectively referred to as "Envelope Teams") can determine the feasibility and merit of these visual studies before proceeding to a higher level of custom visualization.

Although this collaborative approach has been tried in the past, it has rarely succeeded scientifically. These visualization efforts have failed to recognize past experiences and techniques to which scientists are accustomed. Therefore, to achieve a smooth migration to new visual analysis methods through the use of computer graphics, visualization tools must involve traditional representation techniques (plots, graphs, and numerical analysis) as well as object rendering. Only after getting these types of tools in the hands of the researchers and maintaining a dialogue to improve the usefulness of these applications will tough visualization issues involving database management and co-registration of data be resolved properly. This communication process will rely heavily on advances being made in high speed networking, which will play an important role in the promising future of environmental visualization.

Kevin J. Hussey

The Jet Propulsion Laboratory's (JPL's) Digital Image Animation Laboratory (DIAL) and the associated Visualization and Earth Science and Applications (VESA) Group have produced a number of notable environmental visualizations over the past 12 years. Visualization topics have encompassed submarine geology in the Monterey Bay to the Ozone "hole" over Antarctica. Scientific data resolutions ranged from one Angstrom to 345 miles. During the course of producing these visualizations several lessons were learned, difficult issues raised and new technology developed. Examples are highlighted below.

A Lesson: No matter how good, flexible, extensible, comprehensive, powerful or expensive your visualization system (hardware and software) is, it will not perform what the scientist wants. You will have to modify some code to make it happen.

An Issue: Remember the book "How To Lie With Statistics" by D. Huff? If you can lie with statistics then just imagine what you could do with Data Visualization! Sometimes very realistic looking visualizations may be "seeing" things that are not supported by the data. Should we do something about this?

Some Technology: Incorporating technology developed and lessons learned, members of the VESA and Image Analysis Systems (IAS) group at JPL are developing Surveyor, a three-dimensional data visualization system which runs in a heterogeneous distributed computing environment. Surveyor is used by scientists and simulators to analyze and animate a three-dimensional "world". The world consists of a variety of three-dimensional data, such as satellite imagery combined with topography information. In addition to rendering of data, Surveyor can retrieve the original data values for selected areas in a three-dimensional rendered scene. This capability is used as a user interface for the analysis of scientific data, such as geological data bases from desktop computers or across a network to allow use of more powerful machines. Surveyor is utilized as the graphical user interface (GUI) for the Caltech/JPL portion of the Casa Gigabit Network Testbed.

Lloyd A. Treinish

Areas of great interest in the environmental sciences today focus on large-scale data processing and analysis of remotely sensed and in situ data from many instruments and the supercomputer-based simulation of dynamic phenomena. Often these studies involve the integration of the observations with simulations for the creation of empirical models, using the acquired data as input. The structure of these data may be point or sparse, uniformly or irregularly meshed, in rectilinear or curvilinear coordinates, and will consist of many parameters. Visualization is key in understanding these data sets.

Effective visual examination also requires advances in data management. There is no consensus today about solutions to problems involving: addressing inconsistencies and irregularities associated with observational data, maintenance of a connection between image representations of the data and the data themselves, integration of observational data with output from computer models, and scalability to potentially very large size (i.e., greater than one terabyte). One aspect of the data management problem is the ability to uniformly support data of disparate structure, preserve the fidelity of the data (e.g., by noting missing data and original grid resolution), and provide the ability to define coordinate systems onto which different data may be registered in space and time. For visualization tools, data management is important in matching a class of data models to the structure of scientific data and determining how such data is used (e.g., qualitative three-dimensional displays AND precise, analysis and quantitative presentations). In work with disparate data, there is a need to support correlative data analysis providing a common basis for the examination of different data sets in the same way at the same time and providing multiple ways to study the same or different data.

Brian Orland

The author directs a research program in environmental visualization and perception. Research ranges from modeling fishing and ski resort choices, to scenic and policy impacts of forest insect damage. Evaluations are based on calibrated visualizations of forest conditions. Few participants are expert in all scientific areas represented in a forest ecological system. Thus, visualizations must not assume ability to deal with visual abstractions of particular scientific data. Focus is on more realistic visual images than typically found in scientific visualization. A second concern is that a forest scientist, manager, or interested citizen should do more than just respond to pre-planned situations. Our user makes modifications to the visualization and obtains immediate feedback on the implications for data or models.

Software development supports this research and addresses a number of inadequacies in current natural resource scientific visualizations:

(1) Realistic, "concrete," representations of biological models and data support interpretation and evaluation by non- specialists while retaining their validity as data representations.

(2) Data entries and model parameters are manipulated via the visualization and the database is continually updated. Users can participate in forest operations, modify scientific assumptions by direct mouse-click operations, and continually monitor their progress through data summary tables.

(3) Visualizations are truly interactive. Advances in time, changes in viewpoint, and model parameters are viewed immediately — the design criterion is a maximum 3 second delay for display update.

Current work will extend visualizations from thousands of trees to millions of trees, and will distribute model computing to faster machines — such as NCSA's CM5 Connection Machine.

Mike Stephens

The scientific visualization center (SVC) at the U.S. Army Corp of Engineers'' Waterways Experiment Station (WES) assists research engineers and scientists in the six major labs which comprise WES. Since environmental research involves a large number of highly coupled, interdependent processes, these efforts are spread throughout the Hydraulics Lab, Coastal Engineering Research Center, Information Technology Lab, and Environment Lab. The SVC advocates a technology transfer approach. Project researchers and their staffs are exposed to visualization alternatives and then determine appropriate methodologies for displaying their own data sets. The SVC has been active in environmental studies from simple conceptual animations of how a newly designed dredge head will reduce the number of turtles adversely effected during dredging operations to complex interactions of ground water flows on sub- surface contaminants from leaking storage tanks.

Several environmental projects involve not only teams from different WES labs, but also include other research agencies. A project on the management of the United States' largest estuary, the Chesapeake Bay, has research teams from WES hydraulics and environment labs as well as the U.S. EPA and several universities. Perhaps it is the highly interdependent nature of environmental processes that make them particularly challenging to visualization teams to offer solutions which aid researchers to further their understanding. The Chesapeake Bay effort has used visualization in almost every aspect of the project. Techniques for evaluating and editing finite element meshes used in computing hydrodynamics models of the bay were developed. The results from these hydrodynamics models were visualized. Once the models were validated from physical measurements they were used in turn by the water quality group which is concerned with the viability of the bay and the effects that different management strategies have on the bay and the long term results of these newly proposed strategies. This involved the examination of 22 interrelated parameters.

How to Lie and Confuse with Visualization

Chair
Nahum D. Gershon, The MITRE Corporation

Panelists:
James M. Coggins, University of North Carolina at Chapel Hill
Paul R. Edholm, The University Hospital of Linkoping, Sweden
Al Globus,Computer Sciences Corporation at NASA Ames Research Center
Vilayanur S. Ramachandran, University of California at San Diego,

Abstract:
As in other fields such as statistics and cartography, it is also possible to misrepresent data in visualization. Most of the time, people do it unintentionally and it goes unnoticed. But traps await the unwary. The Panel "How to Lie and Confuse with Visualization" will discuss this issue and educate the visualization and computer graphics community about these potential traps. Topics to be discussed in this panel include the use of color, interpolation, smoothing, boundaries, and shading. The panel and the audience will also debate whether there are ways to judge the degree of "lying" in visualization, and how to prevent inadvertent misrepresentations from happening. The panel and the audience will come up with recommendations for "dos" and "don'ts" for the process of creating faithful visualizations. During the discussions and the debates, the panelists and the audience will present many examples of data misrepresentations taken from science, medicine, and art.

Other points include the question if lying with visualization is evil or good and necessary and appropriate in many situations. How much is lying with visualization application-dependent ? Does visual perception have problems or is it very efficient? This point may affect the mechanisms underlying the perception of misrepresentation of visualized data.

The audience and the public have been encouraged to submit samples of slides and video material illustrating visualization "lies." In addition, contributors could bring their samples directly to the session.

Nahum Gershon—"How to Lie and Confuse with Visualization"
Inappropriate use of color could reduce the effectiveness of the results of the visualization process. Color scales without sufficient contrasting regions in the range of values where the data is varying could mask these data variations from the final display. Data structures with shapes familiar to our perceptual system could also create false impressions of the data. For example, if a structure in the data appears as to occlude another it could be perceived as having a higher value than its surrounding area. Colors such as light green and blue are usually perceived as background colors in everyday life. In data visual representation, these background colors could be perceived as representing lower values especially if these regions are large. Crowded color scales, on the other hand, could give too much detail, preventing effective perception of the general trends.

Interpolation (the process used to enlarge the display of small spatial data sets and to eliminate the appearance of the visual annoyance of large pixels) could create the false impression of high spatial resolution. Smoothing (the operation used to eliminate random noise in the data) could make small details disappear.

James M. Coggins —"Lying Toward the Truth"
The challenge of the visualization specialist is to cleverly communicate the truth. Truth can be very, very complicated. Revealing the truth a layer at a time is a reasonable strategy for managing the complexity of the whole truth. Half-truths or even outright fabrications are appropriate and necessary mechanisms for sneaking up on the truth.

Visualization provides new ways to present half-truths that advance understanding toward the whole truth. However, when we begin to rely on the half-truths as if they were the whole truth, crucial aspects of the intended communication can be lost. Hard-edged surfaces of discrete objects make beautiful visualizations but hide the often arbitrary criteria used to form the surfaces. The essential uncertainty in the existence or location of boundaries is masked. Naive interpretations of such visualizations may yield faulty decisions.

Mechanisms for visualizing uncertainty are required to communicate error bars on the measurements that are visualized. Whether the hard-edged visualization is adequate is a question for the application domain client, not for the visualization specialist nor for the visualization system. The visualization system must provide the client with error bars: a sense of when to believe the beautiful, hard-edged rendering and when to disregard or disbelieve it. Examples of how error bars can be visualized will be illustrated. Discussion of other alternatives will be solicited.

Paul R. Edholm —"How the Visual System Interprets Images"
The task of the visual system is to give to the conscious mind a mental representation of the relevant features of the external world. From the flat two-dimensional (2-D) images on the retina, the visual system reconstructs the external three-dimensional (3-D) scene. This is in theory impossible because there are so many 3-D scenes which could yield the same 2-D image. So, the visual system has to try to select the right solution from all the possible solutions. This solution is then presented to our conscious mind as the external world. The mechanisms in the intuitive and unconscious interpretation system of the visual system are in their most part unknown. We only know that they are very complex and highly sophisticated. They probably constitute the most complex structure in the world. But when we see, we are not aware of this. We experience (the illusion) that what we see is a direct perception of the external world. In reality, what we see is a very sophisticated guesswork of the interpretation system.

Boundaries: The boundaries are the most important structures in the interpretation of a picture. Thus, the visual system is more or less developed as a boundary detector and it is a poor judge of density values in a picture. I will discuss lateral inhibition, Mach bands, and illusions caused by lateral inhibition. I will also describe the perception of boundaries and various kinds of boundaries. Boundaries in "natural" images (produced on the retina by real scenes) and images of other kinds (produced on the retina by different artificial means) will be discussed. This will include illusory contours, statistical boundaries, boundaries in X-rays, edge boundaries, boundaries produced by curved interfaces, lamellar boundaries, and illusions caused by curved interfaces combined with lamellas.

Reconstruction of 3-D Scenes from 2-D Images: The clues used by the visual system to reconstruct three-dimensional scenes from two-dimensional images, impossible figures, and 3-D illusions will be discussed.

Al Globus —"Thirteen Ways to Say Nothing with Scientific Visualization"

Scientific visualization should be used to produce beautiful images. Those not properly initiated into the mysteries of visualization research often fail to appreciate the artistic qualities our pictures. For example, scientists will frequently use visualization to needlessly understand their data. I will describe a number of effective techniques to confound such pernicious activity. The audience and the panel will be solicited for additional techniques. The 13 ways are:

1. Never Include a Color Legend
2. Avoid Annotation
3. Never Mention Error Characteristics
4. When in Doubt, Smoothe
5. Avoid Provide Performance Data
6. Quietly Use Stop-Frame Video Techniques

Faithful adherence to the rest of the rules will help avoid tedious debugging of software that already produces pretty pictures.

7. Never Learn Anything About the Data or Scientific Discipline
8. Never Compare Your Results with Other Visualization Techniques
9. Avoid Visualization Systems
10. Never Cite References for the Data
11. Claim Generality but Show Results from a Single Data Set
12. Use Viewing Angle to Hide Blemishes
13. 'This is easily extended to 3-D'

Vilayanur S. Ramachandran—"What Could be Learned from Perception?"

Computers have provided us with new ways of creating visual images from abstract and non- abstract data. Reaching out to the fields of visual physiology, psychophysics, and cognitive psychology could not only explain why human vision is so efficient, but also how to create better images and what could be the limitations of particular representations. The relevance of the knowledge acquired from perception research to the process of creating faithful visualizations will be described. Examples are the areas of stereopsis, perception of transparency, derivation of shape from shading and illusory contours, and color. In particular, I will discuss and illustrate the possible trap of locating the light source in the "wrong" location in simulating shading. I will then specify the situations where the perception of shape from shading could be affected by the location of the light source.

Afterword

Data could be misrepresented in visualization quite effortlessly and inadvertently. The main culprits are perception's complex and intricate nature and the varied experiences of each human being that could make a picture mean different things to different people. Becoming aware of how to lie and confuse with visualization could teach us how to prevent it from happening or at least how to reduce its occurrences.

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The Applications of Evolutionary and Biological Processes to Computer Art and Animation

Panel Organizer: William Latham, IBM UK Scientific Centre
Chair: George Joblove, Industrial Light & Magic

Panel Members:
William Latham. IBM UK Scientific Centre
Karl Sims. Thinking Machines Corp.
Stephen Todd. IBM UK Scientific Centre
Michael Tolson. Xaos Inc.

Abstract
The panel will discuss new techniques for evolving art designs which are based on "Evolution and Biological processes" from the natural world. In particular techniques such a mutation, breeding and selection, marriage, and rules for artificial life animations are discussed. In addition to addressing the advantages and disadvantages of using these techniques, the panel will also discuss their effectiveness as construction and user interface tools for the artist making images, designs and animations.

Background
In general "artistic" computer graphics involves detailed analytical knowledge to specify a design or animation. Often a designer when setting up a geometric structure realizes the huge possible number of variations that can be produced by changing the parameters. Invariably these variations are not explored, even though a variation may be better than the analytically specified design. The reason for this is the vastness of parameter space and time taken to explore it.

Computer Evolutionary techniques allow a more systematic and intuitive exploration of parameter and structure space which allows the user to evolve artistic designs and animations through a method of random mutation, breeding and selection. This allows not just rapid sampling of possible variations but allows a directional and purposeful exploration of variations. This exploration often uncovers possibilities which are beyond the artists'/designers' powers of human visualization, and are arguably beyond their imagination.

These techniques are based on the evolutionary and biological processes in the natural world. They have a major advantages in terms of user interface as they allow the user to interact in a "non-analytic" way intuitively with the computer, so that highly complex models can be evolved. The use of these techniques creates a new style of user interface where the role of the artist can be separated in two: First as "creator" of the Evolutionary system and then as "selector."

This exploits techniques such as simulated annealing, steepest ascent and Monte Carlo optimization. Genetic algorithms borrow from the biological models of genotype (encoding the form), phenotype (expression of coded form), Mutation and sexual reproduction, and selection for simulating evolution. The most exciting effects have been created when these evolutionary techniques have been merged with their own "home grown" growth systems such as Latham and Todd's "Form Grow" or Sim's "Growing Equations." The resulting films are very organic and portray virtual computer worlds operating under alternative evolutionary systems. As the cinema and Virtual Reality's insatiable appetite for the extraordinary increases, these techniques currently being used by a few key experimenters will find their way into the popular domain.

Panel Goal and Issues
The purpose of the panel is to propose the new use of evolutionary and biological concepts as methods for making art and animations and show the unique effects that can be achieved, and try and define their advantages and differences compared to other techniques for artistic design.

The panel will identify the differences in techniques between the work Sims, Latham and Todd and Tolson. Specific techniques such as "structure mutation," "equation mutation," and "automatic offspring selection" will be discussed. Mike Tolson will contrast these techniques with his work with growing brushed patterns using evolution genetic fitness algorithms which use no human user selection.

Having laid down the technical overview, the following types of questions will try to be answered:

* In creating alternative evolutions is this just another manifestation of man's innate desire to create new life as a "pseudo god," or is it a parody of man's manipulation of the natural world through modern technology?
* What is the role of the artist: to be both the "creator" of the system and be the "selector." If these roles are done to by two people who then is the author of the artwork?
* Mutation techniques use randomness, does this make them difficult to use with exact control? or is it possible to mix mutation with analytical techniques?
* In building menu options such as "kill," "breed," or "marry" and applying them to artificial life that often to appear to have a life of their own, does this raise any morality questions?
* What are the future possibilities of these techniques in scientific visualization?
* Latham proposes an Evolution Virtual Reality where the artist would become a "gardener" in an accelerated evolutionary world growing and breeding "giant virtual pumpkins" in "living sculpture gardens," a kind of modern day "Garden of Earthly Delights" (Hieronymous Bosch). What other applications of these techniques in VR could exist in the future.
* Genetic Algorithms have been around for 15 years, is Evolutionary Art just a novel application? What is new?
* When the artist subjectively selects mutations for breeding what criteria are they using? If this can be defined would it not be possible to write a piece of software that could replace the artist?
* Can one label the products of computer evolution art? And if one does, surely then the products of nature should be labeled "art" also in that they also went through an evolutionary process. As Computer Art and Animation become more natural do they become less artistic as the human element becomes less apparent.

William Latham
William Latham will focus on the artistic side of the work and discuss the user interface of Mutator program and outline it's successes and weaknesses as a method for making art.

Latham describes using the Mutator program to be a little like being a gardener breeding, selecting, pruning and marrying forms. The evolved forms look like strange organic sculptural fruits. In the

Mutator program, unlike the natural world, the "natural selection" process is replaced with "aesthetic selection controlled by the artist," so that the process of making art is an explorative evolution steered by the results of aesthetic choices. The evolutionary process helps the artist navigate in an infinite multi-dimensional parameter and structure space to find artistic forms.

Latham argues that when using the "mutator" program the computer ceases to be like a tool but is more like a creative partner where the artist is continually surprised by the results which are automatically produced. This close interaction between artist and machine produces unexpected and strange results.

Recent work has involved inventing "Life Cycle" rules to create organic animations showing chains of living, breeding and dead mutations gradually forming vast colonial formations.

Latham will discuss the problems of setting up "artificial animations" and in particular the "Life Cycle" rules. He will also identify some of the artistic issues in the work such as randomness, the balance of power between artist and machine, displaying the artworks in the gallery world and its position in 20th Century Modern art.

Stephen Todd

Stephen Todd will discuss the program Mutator as a user interface tool. Mutator is a tool to assist a user in a search of a multidimensional parameter space. The computer makes moves in space and displays the results of these moves, and the user selects the results that are liked.

Mutator can be looked at as a computer implementation of the process of natural selection, with the mutation process performed by the computer and the selection by the user. Alternatively, it can be looked at as an optimization process, with the cost function provided by the user.

Mutator gives the user a variety of ways to control the movement in parameter space.

- The simplest is random mutation of the parameters.
- The simple random search can be directed by judging some of the available choices as 'good' or 'bad.' These judgments set up a direction of movement, similar to the use of hill climbing in optimization.
- Finally, preferred objects can be 'married' to create new objects that use a mixture of the parameters of the parents.

The augmentation of random mutation by judgment and marriage considerably enhances the speed and effectiveness of Mutator in reaching interesting areas of the search space.

The primary advantage of Mutator is that it permits the user to search using *subjective* decisions. This contrasts with more conventional user interface tools, which make it easier for the user to carry out *analytic* decisions.

Todd will discuss the potential for Mutator as an interface in other applications such as scientific visualization, economic modeling and the generation of 'identikit' pictures by witnesses.

Karl Sims

Karl Sims will present several applications of interactive evolution. The evolutionary mechanisms of variation and selection are used to "evolve" equations used by various procedural models for computer graphics and animation. The following examples will be briefly discussed and results from each will be shown:

- Procedurally generated pictures and textures
- 3D objects defined by parametric equations
- Dynamical systems described by differential equations.

Each uses hierarchical lisp expressions as "genotypes" to define arbitrary equations which are evaluated to create resulting "phenotypes." The equations and their corresponding phenotypes can be mutated, mated, and interactively selected to search "hyperspaces" of possible results. A comparison between evolving values of parameter sets and evolving arbitrary length equations will be made.

"Genetic cross dissolves" can be used to create smooth interpolations between evolved entities. Their use in creating the animation "Primordial Dance" will be described.

It is proposed that these methods have potential as powerful tools for exploring procedural models and achieving flexible complexity with a minimum of user input and knowledge of details. Complex equations can be efficiently found that might not be easily designed or even understood by humans alone.

Mike Tolson

Michael Tolson will talk about his recent work evolutionary and biological techniques: He is creating "eco systems" of many simple "animals" which are visualized by brush strokes. Their behaviors are controlled by neural networks (their "brains") which are a part of the genotype and can be evolved. The animals use up energy by moving and can gain energy by performing appropriately, for example moving towards a light. They can interact with their environment in various ways and can achieve "biological" effects such as phototropism and reaction-diffusion like systems. He is not using interactive selection, but instead the more traditional genetic algorithm approach with defined fitness functions. He is however, more interested in creating "art" than in the scientific details of the process.

Summary Statement

The aim of the panel is to give an overview by leading exponents, contextulise their work, to provoke discussion and be provoked.

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Urban Tech-Gap: How the Museum/University Liaisons Propose to Create a Learning Ladder for Visual Literacy

Chair: Richard Navin, Brooklyn College, City University of New York

Panelists:

Lynn Holden, Carnegie Mellon University

Edward Wagner, The Franklin Institute Science Museum

Robert Carlson, Director, Tech 2000: Gallery of Interactive Multimedia

Michael McGetrick, Brooklyn College

Summary

Universities and public education are putting the creative means of professional multimedia production into their own hands. Science and industry museums engaging media as producers now offer serious instructional visualizations through creative hands-on components drawing visitors into active participation. The distance is closing between museums' high-calibre productions and educational usage through open electronic toolboxes in the individual classroom. Yet a severe dislocation exists between the producing centers and the decay in their immediate environment — the inner city.

Collaboration bridges strengths and resources from two methodologically different environments. This panel seeks to place a bridge between the differences of these two professional worlds and develop a ladder for visual literacy as a common domain.

Issues Under Discussionn

- The finest science and industry museums exist in midst of the worst financially-blighted urban centers the most abandoned urban school districts. Are minority-dominated, overcrowded classrooms unable to come to grips with, or understand in a rudimentary fashion, rapidly advancing technology linguistics — particularly when their computer labs are crippled or virtually non-existent? Tax-levied education faces increasing draconian budgets for three to five year. How can tools and multiculturalism be integrated with the means at hand?
- What curriculum bridges can be created in advance of exhibitions? What social components should determine their final form? Between usage and exhibit production values, can a more sensitive awareness enter "opening the architecture" and creating tools that bridge the discontinuity between high-level productions finished in a museum "Hollywood" setting and real learning? What is needed are forms that transmute content through "the language of the street" — forms understood by the average (and deprived) urban public school classroom and those students snarled in its chaos.
- Why are most high-quality, master computer centers distanced (safely) from the largest inner city school districts? Should high-tech be physically downloaded into some form for urban equilibration following the marketing of GI Joe, comics, pop-up books, music or rap oriented materials? This is such an untried avenue that we cannot even begin to believe we approach "separate but equal" social segregation.
- Downloading: High production values in themselves induce passivity (i.e. the "Carl Sagan" approach gives us very high, but passive values on the edu-tainment meter). Few projects of meaningful application are developed in the argot of the children watching. Nothing induces vocational interest or offers access to a science career in a designated spot within the viewer's interactive participation and behavior modeling. Should productions including some staffing role that incorporates "human tools" drawn directly from the disenfranchised and underprivileged where we deem to do good?
- Do exhibition, production-value approaches too easily adopt a TV cultural fast-food pace and too speedily send viewers on their way?

At the museum level, sheer numbers of viewers and the fifteen minute message are determined by large attendance traffic necessities. At the schools, amateurism often mars the connectivity of video, hypertext, and programming, detouring the expectations of visually astute and sophisticated youths. Educators and museum program designers on this panel offer real links between visitor/learners and serious instruction. Written materials can support strong visuals and supply stick to the ribs knowledge in the wake of video flash. The dialogue between panelists contrasts the style and formatting problems of exhibiting and instructing and offers a "how to" on establishing usage between museum educational institutions and visually attractive teaching modules, while still downloading qualified and deep instruction without losing the sweep and verve of highly attractive visualization.

Lynn Holden: The great pressing need is how to link and move forward the existing elements of the multimedia matrix. The human, hardware and software components all exist, but they are dislocated and without adequate resources and financial support from government, industry and local communities/institutions.

If there is not a concerted effort, cooperatively between universities, non-profit institutions and industries to set high quality standards in new applications and products, the near-term ramifications will be disastrous for us as professionals, for our organizations and for out culture!

We must create and support an effective, functional network for developers and creative individuals working on new multimedia and interdisciplinary project, and facilitate completing and making visible actual examples which address short and long term issues.

Ed Wagner: The Cutting Edge Gallery presents new technologies and products to a wide range and intellects. As gallery coordinator I procure these devices and have to quickly learn how to operate them and understand the technology, then present this information to the visitor. The challenge is to take complex scientific information and translate it into a form that is comprehensible to the lay person. The Gallery, like other areas within the Franklin Institute, transfers this knowledge to wide range of visitors while in an informal setting.

Richard Navin: One clearly sees across the audiences of all national conferences a lack of color... minorities are no where to be bound in a significant population as makers of multimedia except as strategically marketed talking head so news shows and sit-coms. City University of New York is woefully behind in adapting the media-designing computer to its constituency — the representation student population. In some small but significant way Image and Communications Projects now place students in design roles with government-aligned agencies. Our next step from the advantaged position of a new Media Center created by a new administration is to begin electronic publishing. We have reasonable found self esteem. We now need to advance into an articulate electronic venacular.

Virtual Reality and Computer Graphics Programming

Chair:
Bob C. Liang, IBM T. J. Watson Research Lab

Panelists:
William Bricken, University of Washington
Peter Cornwell, Division, Inc.
Bryan Lewis, IBM T. J. Watson Research Lab
Ken Pimental, Sense8 Corporation
Michael J. Zyda, Naval Postgraduate School

Virtual Reality provides a multi-sensor 3D human machine interface. VR applications requires system software interface to various input/output devices, e.g. tracker, glove, head mount display, sound, speech recognition, etc., and a programming environment for building and interacting with the virtual world.

We are addressing software issues of Virtual Reality related to computer graphics: the building of the virtual world, and the management of its underlying data structure; the communication software issues in building a cooperative virtual world environment; and the issues in programming the interaction in the virtual world.

Michael J. Zyda: The Software Required for the Computer Generation of Virtual Environments

The first phase of virtual world development has focused on the novel hardware (3D input and 3D output) and the "cool" graphics demo. The second phase of virtual world development will be to focus in on the more significant part of the problem, the software bed underlying "real" applications. The focus of this talk is on the software required to support large scale, networked, multi-party virtual environments. We discuss navigation (virtual camera view point control and its coupling to real-time, hidden surface elimination), interaction (software for constructing a dialogue from the inputs read from our devices and for applying that dialogue to display changes), communication (software for passing changes in the world model to other players on the network, and software for allowing the entry of previously undescribed players into the system), autonomy (software for playing autonomous agents in our virtual world against interactive players), scripting (software for recording, playing back and multi-tracking previous play against live or autonomous players, with autonomy provided for departures from the recorded script), and hypermedia integration (software for integrating hypermedia data-audio, compressed video, with embedded links —into our geometrically described virtual world). All of this software serves as the base for the fully detailed, fully interactive, seamless environment of the third phase of virtual world development.

William Bricken: Virtual Reality is Not a Simulation of Physical Reality

One of the weakest aspects of current software tools for VR is that designers are bringing the assumptive baggage of the world of mass into the digital world, undermining the essential qualities of the virtual. Information is not mass; meaning is *constructed* in the cognitive domain. Psychology is the Physics of VR. In building virtual worlds, we are continually discovering that they are strongly counter-intuitive, that our training as physical beings obstructs our use of the imaginary realm.

The greatest design challenge for VR tools is mediating between physical sensation and cognitive construction. VR software must directly resolve the mind-body duality which plagues both Western philosophy and computer languages. VR calls for a philosophy of *immaterial realism*. VR doesn't matter, it informs.

I will briefly describe a new generation of software tools which emphasize virtual rather than physical modeling concepts. VR tools are situated, pluralistic, synesthetic, paradoxical, and most importantly, autonomous. Their programming techniques include behavioral specification (entity-based models), inconsistency maintenance (imaginary booleans), possibility calculi (set functions), relaxation (satisfying solutions), experiential mathematics (spatial computation), participatory programming (inclusive local parallelism) and emergence (realtime non-linear dynamics).

Peter J. Cornwell

Division Inc. is a VR systems company which has supplied hardware, software and integrated systems products to application developers and end users worldwide for over three years.

Research and commercial applications of VR in the fields of pharmaceutical engineering and marketing, landscape architecture, industrial furnishing and lighting will be described and the evolution of installed hardware and software briefly reviewed.

The important trends arising from these installations will then be identified with particular emphasis on:

1. protection of investment in applications development through portability across a range of different vendor and performance hardware configurations.
2. interfacing VR facilities with existing computer systems and software

Finally, current and proposed developments to address the evolving VR marketplace will be covered.

Bryan Lewis : Software Architecture

Virtual Reality applications are difficult to build, involving multiple simultaneous input and output devices, complex graphics, and dynamic simulations, all of which have to cooperate in real time. If a simulation expert wishes to imbed a complex simulation or model into a virtual environment, one approach is to add functionality one call at a time to the existing simulation code. This appears to be the easy way to get started. But simulations are already quite complex, and adding code for multiple devices and multiple machines can become unwieldy. The problem is made worse by the fact that simulation experts generally do not have the time or inclination to learn a book full of user interface calls.

A better approach is a "minimally invasive" software architecture that allows the simulation to be connected to the rest of the world without surgery. Such an architecture hides the complexities of connecting the simulation to other modules on other machines. This provides the foundation for a useful tool kit; to that must be added a kit of ready-to-reuse modules (for various devices and interaction techniques), and graphical tools to assist in building the world.

Kenneth Pimentel : 3D Graphics programming simplification
I would discuss how the process of interacting and creating a 3D simulation can be drastically simplified by using an object-oriented graphics programming language. I will also mention how this approach provides the utmost in flexibility which is critical in an emerging field. No one knows the "right way" to do things. Experimentation, rapid prototyping, and flexibility are key.

I will contrast the benefits and trade-offs of a graphic oriented interface versus a programming interface for the creation of virtual worlds.

I will bring a video tape showing various types of simulations created using WorldToolKIt. This will show the audience the diversity of applications already created.

Ubiquitous Computing and Augmented Reality

Chair:
Rich Gold, Xerox PARC

Panelists:
Bill Buxton, University of Toronto & Xerox PARC
Steve Feiner, Columbia University
Chris Schmandt, M.I.T. Media Labs
Pierre Wellner, Cambridge University & EuroPARC
Mark Weiser, Xerox PARC

" The door refused to open. It said, 'Five cents, please.' He searched his pockets. No more coins; nothing. "I'll pay you tomorrow,' he told the door. Again he tried the knob. Again it remained locked tight. 'What I pay you,' he informed it, 'is in the nature of a gratuity; I don't have to pay you.' 'I think otherwise,' the door said. 'Look in the purchase contract you signed when you bought this conapt.' "

-Philip K. Dick, from "Ubik"

Panel Background
Ubiquitous Computing is a radical alternative to the desktop and virtual reality models of computing. It turns these models inside out: instead of using computers to simulate or replace our common physical space, computers are embedded invisibly and directly into the real world. Everyday objects and our normal activities become the I/O to this highly sensuous and reactive environment. Objects are aware of and can respond to the location, state and activities of other objects in the world, both animate and inanimate. The implications are important: computing should be part of our everyday existence rather than isolated (and isolating) on a desktop; of equal importance, computer-based systems can take advantage of, and be compatible with, the rich environments in which we live. The poverty of the workstation, with its limited display, array of keys and single, simple pointing device (bad for the eyes, bad for the back, bad for the marriage) becomes clear when designers try to integrate it into our complex social and physical environments.

Panel Goals
The July 1993 issue of the Communications of the A.C.M., co-edited by Pierre Wellner, Wendy Mackay and Rich Gold, explores the research fields collectively known as Augmented Environments. This panel brings together five visionaries within this field to look at its implications and future. Each member is an expert within a different domain including ubiquitous video, projected reality, augmented reality, ubiquitous audio and infrastructure. Combined, these areas create a powerful new way of interacting and living within a computational environment. After a brief overview, each panel member will present a perspective on their own work in the field. Following these presentations panel members will have an opportunity to discuss the over-arching features of ubiquitous computing and answer questions from the audience.

Bill Buxton
Work in UbiComp has been paralleled by work in Video "Mediaspaces." Our position is that in such Mediaspaces, it is just as inappropriate to channel all of one's video interactions through a single camera/monitor pair; as it is to channel all of one's computational activity through a single keyboard, mouse and display. This leads us to the notion of Ubiquitous Video, which parallels that of Ubiquitous Computing.

When UbiComp and UbiVid converge, all of the transducers used for human-human interaction are candidates for human-computer interaction. Hence, for example, your computer can "see" you using the same camera that you use for videoconferencing, and it can hear you using the same microphone that you use for teleconferencing. These are not just changes in the source of input, however. They imply important changes in the nature of information available. Traditional human-computer dialogues have focused on foreground "conversational" interaction. Much of what will emerge from this Ubiquitous Media environment is much more similar to remote sensing. What is provided is background information about the context in which conversational interactions take place. It is this bimodal foreground/background interaction which we will pursue in our presentation.

Steve Feiner
Virtual reality systems use 3D graphics and other media to replace much or all of the user's interaction with the real world. In contrast, augmented reality systems supplement the user's view of the real world. By adding to, rather than replacing, what we experience, an

augmented reality can annotate the real world with additional information, such as descriptions of interesting features or instructions for performing physical tasks. For this supplementary material to be as effective as possible, we believe that it should not be created in advance, but should rather be designed on the fly using knowledge-based techniques that take into account the specific information to be communicated and the state of the world and user.

To test our ideas, we have been building an experimental, knowledge-based, augmented reality system that uses a see-through head-mounted display to overlay a complementary virtual world on the user's view of the real world. In a simple equipment maintenance domain that we have developed, the virtual world includes 3D representations of actual physical objects and virtual metaobjects such as arrows, textual callouts, and leader lines. A knowledge-based graphics component designs the overlaid information as it is presented. The design is based on a description of the information to be communicated and on data from sensors that track the position and orientation of the user and selected objects.

Chris Schmandt

Communication is what needs to be ubiquitous. "Computing" is what will provide the backbone to allow transparent mobility, and, perhaps more important, filter or control access so we do not get overwhelmed with all the stuff that comes down the pipes at us. Communication is even more about voice than it is about text and/or graphics. Ubiquitous computing has to handle voice! Voice interfaces may let me wander around my office and interact with computers through a window larger than that provided by a 19 inch display. Voice is how my environment will communicate with me as I move through it in the course of a work day. Voice is what will let us miniaturize devices below the sizes of buttons and displays.

The pocket phone provides a highly mobile computer terminal with today's technology. Telephone access to email, voicemail, my calendar and my rolodex, as well as various online information services, has already begun to change the way my group works. Wireless digital telephone networks using low powered pocket transceivers are inevitable. Although these are usually touted as "Personal" Communication Networks, telephone service providers have never understood that personalization requires dynamic decisions about how to route communication, and cannot be expressed as static routing tables in a telephone switch. Here's where the "computing" comes in — deciding which calls (or which email for that matter) will make it through my filters to ring the phone in my pocket.

Mark Weiser

A technological response to the challenge of making life better is to radically reconceive the computer around people's natural activity. Two key points are: people live in an environmental surround, using space, muscle memory, 3-D body surround; and that people live through their practices and tacit knowledge so that the most powerful things are those that are effectively invisible in use. How can we make everyday computing conform better to these principles of human effectiveness?

Our approach: Activate the world. Provide hundreds of wireless computing devices per person per office, of all scales (from 1" displays to wall sized). We call it: "ubiquitous computing" — and it means the end of the personal computer. These things in the office, every place you are, are not workstations or PC's. You just grab anything that is nearby, and use it. Your information and state follows you; the hundreds of devices in your office or meeting room adjust to support you.

Pierre Wellner

What is the best way to interact with computers in our future offices? We could make workstations so powerful and so versatile that they integrate all our office activities in one place. Or, we could make virtual offices that could free us from all the constraints of the real world. Both of these approaches aim to eliminate the use of traditional tools such as paper and pencil, but my position is that we should do the opposite. Instead of *replacing* paper, pens, pencils, erasers, desks and lamps, we should keep them and use computers to augment their capabilities.

Let's take paper, for example. Screen-based documents have not (and will not) replace paper completely because, despite its limitations, paper is portable, cheap, universally accepted, high resolution, tactile and familiar. Like with many traditional tools, we hardly think about the skills we use to manipulate paper because they are embedded so deeply into our minds and bodies. A lot of effort goes into making electronic documents more like paper, but the approach I propose is to start with the paper, and augment it to behave more like electronic documents. With a projected display and video cameras that track fingertips and tools, we can create spaces in which everyday objects gain electronic properties without losing their familiar physical properties. I will briefly discuss work to date on a system that does this: the DigitalDesk. I will also show some future envisionment videos that illustrate more ideas for how we could augment (instead of replace) paper, pencils, erasers, desks and other parts of the traditional office.

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Electronic House, published bi-monthly by Electronic House Inc.

Merging 3-D Graphics and Imaging - Applications and Issues

Chair
William R. Pickering, Silicon Graphics Computer Systems

Panelists:
Paul Douglas,Earthwatch Communications
Kevin Hussey, Jet Propulsion Laboratory
Michael Natkin, Industrial Light and Magic

There are many applications that require both image processing and 3D graphics techniques. The panelists present application specifics and demonstrations of how image processing and 3D graphics are used together, and why these applications cannot be solved without the use of both disciplines.

Panel Background

Computer graphics and image processing were once two very distinct disciplines, with different hardware, software, and users. Now they are becoming increasingly intertwined. Applications are being developed that use both 3D graphics and imaging techniques for a broad spectrum of uses, including realistic scene simulations, interesting visual effects, and improved analysis and understanding of complex information. What should graphics users learn from their imaging counterparts, and vice versa? This panel brings together people from both disciplines who have been developing a variety of applications that merge graphics and imaging technologies. They will illustrate both the benefits and current limitations.

Panel Goals and Issues

Many applications require the use of real-world data most often obtained from sensors in the form of images. To view the data in the three dimensional space that it was obtained from, 3D graphics techniques are often used. How is image data transformed into a 3D view? The solution has been approached from both the image processing and 3D graphics disciplines.

Image processing technology is used to take real-world image data and process it into an image that highlights desired features. The final image can then be used in conjunction with 3D graphics techniques to render a 3D scene.

How are images used in conjunction with 3D graphics techniques to create more realistic views? What image processing techniques are used to enhance the image before rendering? How can images be utilized as sources for 3D models? How can 3D graphics techniques be used to view the image data?

The panel will offer discussion and demonstrations of how image processing and 3D graphics are jointly used to create 3D scenes from 2D images. Questions from the attendees will be answered during the concluding portion of the session.

Kevin Hussey

Kevin will describe the image processing techniques necessary for texture map preparation in the context of a complex scientific visualization entitled "Monterey: The Bay". The visualization simulates a flight through the Monterey Bay environment (above and below the ocean surface) using seven different geophysical data sets. Data from a numerical model of ocean currents were interpolated into sufficient time intervals for a smooth animation. Sets of polygonal "ribbons" were created to visualize the current flow. These ribbons were then rendered, anti-aliased and composited into a perspective ray-cast scene comprised of 3 additional image data sets.

Paul Douglas

Paul will describe a weather graphics system that he has developed and uses to provide visuals for his nightly weather broadcasts. The system transforms flat, 2-D pixel imagery of clouds and radar data into 3-D geometry allowing the viewer to view weather from multiple perspectives. The system merges images, ingested from live weather feeds including geostationary weather satellites over the Pacific, Europe and North America., with a full GIS system containing data from all over the world, to create a 3-D model. Weather phenomena is supplemented with imagery from SPOT, Landsat or aerial photography for enhanced realism.

Michael Natkin

Successful special effects depend on the seamless integration of computer generated objects with live action environments on film. Two-dimensional image techniques are a critical component of Industrial Light and Magic's production process. Michael will describe the use of painting, digital compositing, color balancing and edge quality adjustment, wire removal, image warping (morphing), texture projection, and 3D painting in movies such as *Terminator 2* and *Jurassic Park*. He will also discuss the future of special effects image processing, design of software for special effects production, and system hardware and software performance requirements.

Nan-o-sex and Virtual Seduction

Co-chairs:
Joan I. Staveley, Artist/Educator
David Steiling, Ringling School of Art and Design

Panelists:
Paul Brown, Mississippi State University
Michael Heim, Philosopher/Author
Jill Hunt, Angel Studios
Chitra Shriram, Xaos Inc. and The Ohio State University

Goals and Principle Issues

Among the principal issues the panel should address are:

1) Is virtual space really interactive or merely voyeuristic?
2) What are some of the alternatives to classic male erotica that might unfold within the possibilities of virtual space?
3) Who will be constructing the space? Who will be the audience? Who will be the target market?
4) Who/what are the real subjects and objects in virtual eroticism? How are the subject and objects constructed?
5) Is virtual reality a challenge or an aid to the development of better understanding and relations between the genders?
6) Is Cartesian coordinate space "neutral" or is it, like language, male-constructed?

The purpose of the discourse is not to add to cross-gender recriminations or to arrive at satisfactory conclusions, but to start a discussion based on the inevitability that eroticism is one of the first uses to which virtual reality is being put.

Panel Background

This panel is organized to apply some of the techniques and positions of recent criticism to virtual reality and computer graphics. The panel is committed to doing this in a manner that would avoid much of the jargon that can make such discussions hard to follow. The panel also wishes to avoid moral judgments on the subject being discussed in favor of allowing a plurality of voices to be heard on this controversial topic. Among the positions that will inform the discussion are those of feminism, deconstruction, Marxism, and a number of other post-modern critical attitudes. Among the assumptions of the panel is that, like it or not, virtual reality eroticism is going to be with us, and is in fact avidly anticipated.

Paul Brown

Some have proposed that we can expect virtual realities that are as 'fine grained' as physical reality by the year 2000. At this point our whole appreciation of "the natural world" may well break down. Instead of a defined reality, with myriad imaginary worlds, we will have a continuum of potential realities where the 'real' reality will have lost any particular significance. Our model is the renaissance period when the planet Earth changed from the center of the universe to an undistinguished speck in an unremarkable galaxy in an inconceivably vast and growing universe. The sexual implications of this breakdown of reality are tantalizing. The likely result is a tight symbiosis which will include humankind and their machines—virtual sex will be existentially 'real sex' where mutual human activity will be only one manifestation, distinguished perhaps only by the amount of mess it makes. Researchers report that women prefer linguistic eroticism while men prefer visual (Iconic) forms. The new eroticism with its immersive, symbiotic qualities may well bridge the gender gap. A lot will depend on who controls it. If it is developed within the traditional male hierarchical power structure it could become yet another form of constraint; however, the networks that will enable this evolution have an intrinsic matriarchal hetrachical quality. The growing number of technical conferences which have responded to the need for critical discussion of human/gender oriented issues is evidence of a move towards a more humanistic mode of enquirey.

Michael Heim

Primitive VR has become a screen on which we project our fantasies, both collectively and individually. Soon, the entertainment industry will sell gender-based sex fantasies for virtually safe sex. But the hazards of teledildonics will trap sex in the same voyeuristic cage that imprisoned painting, the novel, and cinema. Computer-generated realities have sprung from a deep erotic drive to see, hear, touch, and be touched by a perfect, knowable world. The thrill of speed, the elan of flight, and the freedom of a liquid self have attracted humans for centuries. Plug this Eros into electronics, and you think you can have it both ways, keep a distance while at the same time put yourself on the line. Beyond gender voyeurism moves a freely active and self-aware body that revels in the flow of internal energy without genital fixation. VR could eventually become a tool for training and sharing this body of spiral energy. Rather than a corpse dangling in frustration while trying to 'have it both ways,' the old erotic body may learn to move and love in entirely new ways.

Jill Hunt

Currently VR, in terms of eroticism, is purely voyeuristic. In the future, VR gender-independent interactive spaces could be used a creative outlet to help bridge the gap between the sexes, particularly in the workplace, creating a more direct method of communication and information exchange. By developing gender-independent spaces we might also risk repressing gender awareness altogether; therefore we must also develop gender-dependent experiences and exchanges in order to further our awareness of ourselves and the opposite sex. There is room for more variety of expression than is currently predominant in our male dominated society, although it will take time to develop and educate people on the benefits of this exposure. Repression is imbedded in our society and directly related to gender discrimination and sexuality. The current and confused view of repression causes many problems that I feel can be work out in VR.

Chitra Shriram

Battles for power, money and ideology rage about the still largely anticipated phenomena of virtual reality. An ancient myth comes to mind. Gods and Demons had once grown so powerful that neither could gain and advantage of the other. Each side strove to prevail by drinking the nectar of immortality that flowed deep in the ocean depths, so Gods and demons together began to churn the ocean. Incredible gifts spewed forth and both nectar and poison rose to the surface of the water, inviting consumption. The god Shiva drank the poison, arresting the evil in his throat. He saved the world from destruction. The God Vishnu, disguised as an enchantress, lured away the demons so that the Gods could create good with the life-giving nectar.

We barely know what poisons or nectars we court. The very notion of looking to ancient spiritual disciplines to inform us on how and what we could do with our latest scientific and technological feats is likely to sound ludicrous—tolerated only in the convenient name of 'multiculturalism.' But the very absurdity of the exercise is warranted by an urgent need to widen the base of value systems which nourish this new manifestation of our psychic and technological desire and energy.

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Critical Art/Interactive Art/Virtual Art: Rethinking Computer Art

Chair:
Timothy Druckrey, International Center of Photography

Panelists:
Regina Cornwell, Independent art critic
Kit Galloway, Electronic Cafe International
Sherrie Rabinowitz, Electronic Cafe International
Simon Penny, Univerisity of Florida
Richard Wright, University of London Polytechnic

Richard Wright:
This essay explores how scientific knowledge is diffused into society through the medium of scientific visualization, taking the late eighties phenomena of *Chaos Culture* as an example.

Beginning with Peitgen and Richter's initial popularization of fractals in their *Frontiers of Chaos* exhibition and catalogue, we study readings of Chaos Theory and Fractals from the scientific to cultural critiques like Vivian Sobchack's article in [Art Forum,] and popular media forms in youth magazines and 'style' culture. This provides us with an overview of many interpretations of this science from the cynical to the mystical and how it captured the public's imagination.

Donna Haraway's study of how to contest scientific knowledge or stories for the creation of public meanings in relevant here to the extent that it shows a way in which we can critique the cultural impact these scientific concepts on the basis of their scientific credentials directly. A difference here is that the situation is complicated by the mediation of the Chaos story by imagery and media. This has many arguable effects such as obscuring the scientific background or conversely making it more 'accessible,' and by creating a conflict between critical scientific readings of scientific discourses through imagery and aesthetic readings of them. The latter problem is most pressing in the context of scientifically related graphics that are presented in the context of Art. We conclude that a deeper level of cultural readings of scientific visualization are needed, especially in the context of art, readings that address scientific discourse more thoroughly and attend to how it now operates through imagery to take effect socially and politically.

Kit Galloway & Sherrie Rabinowitz:
If you look at the aesthetic quality of the communication and you're true to your art form and your art logic, then you very naturally put one foot in front of the other and get to these places. The art logic marches you right out the art institutions into life. From "Defining The Image as Place: A Conversation With Kit Galloway, Sherrie Rabinowitz & Gene Youngblood," High Performance Magazine #37, 1987.

If the arts are to take a role in shaping and humanizing emerging technological environments, individuals and arts constituencies must begin to image at the much larger scale of creativity.

We must begin to create at the same scale as we can destroy, or else art, and more dangerously the human spirit and imagination, will be rendered decorative and impotent.

If the boundaries between art and life dissolve, it will be the result of artists migrating towards a new order of artmaking, abandoning the conventional standards and practices and becoming 'new practitioners' or systems integrators, who produce situations, contexts, and permanent environments or utilities. The 'new practitioners' can begin the process of healing and aesthetic wound that has disfigured the business of Art, and continue the aesthetic quest in more relevant directions.

New creative activities must emerge such as multi-media creative solutions networks, not simply computer networks for Artists, but rather multi-media telecommunications networks with agendas that can engage multi-disciplinary constituencies. This will require the development of new skills and the cultivation of new relationships between the participants. The movement is towards the control of a meaningful context, creating environments not just to support art, but that create the possibility for new scales of creativity across all disciplines and boundaries.

The dark side of the "new world information order" suggests that a new scale aesthetics be created. It will take several years from the time this work begins for creative solutions networks of appropriate number, scale, velocity, and dexterity to evolve to maturity. Consider: co-creating non-imperialistic, multi-cultural or domestic agendas for community or global scale aesthetic endeavors. Consider: the continuous re-invention of non-hierarchical telecom networks that will allow people to bypass cultural gatekeepers and power brokers. We must accept these kinds of challenges and recognize what can be gained by solving them.

All of this implies that there is a new way to be in the world. That the counterforce to the scale of destruction is the scale of communication, and that our legacy or epitaph will be determined in many ways by our ability to creatively employ informal, multi-media, multi-cultural, conversational, telecommunications and information technologies.

Tim Druckrey:
If images are to become increasingly experiential, then a theory of representation must be evolved to account for the effects of a new form of transaction with art. The issues raised by the convergence of technology and creativity are crucial. Interactive art will require a complex reassessment of the relationship linking experience and discourse. At the core of this fundamental shift in the development of both communications and art is the ability of the digital media to encompass text, still and moving images, feedback systems, sound, animation and simulation. How the effects of this integrated model of creative production is joining with the development of content is an essential component in the development of interactive art.

For some time the definition of interactivity has been something of a rote signifier of hands-on activity. Yet the relationship between behavior and the concept of interaction are not so easily resolved. Interactive technologies need to be linked with both cogent content and flexible form. However, a simplified concept of the interactive cannot suffice to fructify this complex and dynamic field.

Interactive media is now wildly touted as the creative medium for this decade. What is not articulated in this equation is the demand made on both producer and recipient of this panacea. The equipment and resources necessary for this media too easily limit both its accessibility and its audience. Whether multimedia will reach it intended audience or not is hinged on a market that should stabilize enough for users to invest in it. Unfortunately, too much multimedia reaches the market as either prepackaged or as marginal.

Art that demands more than visual attention will refocus criticism on the issues of experience. Because interactive works begin to pose the problem of the breakdown not the meaning but of a certain concept of order grounded in ideas of unity and form, they propose an alternative unity. Non-linear principles of organization, in fact, are the signifier of a culture accustomed to fragmentation and montage. Information in this environment comes as an array rather than as a sequence. Deciphering the array — or even producing the array — is a challenge that must be accompanied by considered conceptual and theoretical practices. Lingering narrative concepts, simplistic montage, and furtive use of digitized video and television cannot substitute for expressive order. Intention must become reciprocal. While this endangers the authorial position of the producer, it simultaneously must account for an audience willing to investigate the space of electronic expression.

Regina Cornwell:
Art made with the computer means the end of the unique object as it has been traditionally conceived of and cherished in the art world. Fine art museums exist to collect, preserve and exhibit unique objects. As institutions they flourish on concepts such as originality, the individuality of the artist, genius, the trace of the artist's hand. An entire language exists to support such thinking and concepts.

What place do objects such as interactive computer installations and flat wall pieces, made with a computer, have in the fine arts museum now? But more importantly, what place will they and museums gives us? What might the future hold for art made with the computer? Film and photography are mechanical forms from the nineteenth century. One can find lessons in both their histories within the fine arts museum, yet cinema as an art form suggests more challenging issues which seem closer to art made with the computer than does the area of traditional photography.

Art and the computer exist in distinctly separate worlds, each with its own vocabulary, sensibility, culture, and economics. What can and will bridge the gaps between these two worlds in order to open up dialogue and new possibilities?

Simon Penny:
Simon will serve as a respondent to the panel.

Digital Illusion: Theme Park Visualization

Chair:
Clark Dodsworth, Rising Star Graphics, Ltd.

Panelists:
Kevin Biles, KBD Innovative Arts
Richard Edlund, Boss Film Studios
Michael Harris, NCR/AT&T Human Interface Technology Center
Phil Hettema, MCA Recreation Services
Mario Kamberg, MCA Recreation Services
Brenda Laurel, Interval Research Corporation
Sherry McKenna, Rhythm & Hues
Allen Yamashita, Entertainment Design Production Group

Panel Background

As entertainment delivery systems become digital, a major venue for large interactive visual databases will be theme parks and LBE (location-based entertainment) facilities. What new expressions in the existing set of theme park experiences can digital imaging and sensing provide? The present state-of-the-art might be non-interactive attractions using 70mm films, often showing CG integrated with live action. Some of this imaging is seamless hyperreality; some is grounded in the fantasy worlds of traditional cell animation. These experiential installations are typically unique, expensive, and exciting in ways not previously possible. As cost decline for hi-res real-time rendering, actual audience participation and interaction will be incorporated in attraction scenarios that are, by their very design, user interfaces. Such recreational interfaces are at one end of a scale which extends to handheld videogame platforms at the other. There will eventually be systems with multiuser telecommunications between the two. Panelists will show footage form their attractions in the parks around the world and discuss issues of creative development, system design, visualization tools, cost per park attendee per hour, interactivity, licensed properties, appropriate technology, the search for better illusions, and the art of telling a good story.

Michael Harris

Location Based entertainments (LBE) reflect the cutting edge of our industry, where convincing sensory illusions and natural interactivity can translate directly into fascination and profit.

We focus on 70mm, simulation, full motion HDTV, networking, cyberspace, virtual reality.... But these are all adjectives. Will players embrace this high-end media stuff? Pay for it? Enough to convince owners and operators to invest in it? The key issue is likely to be: what will players do with it all? What will the *nouns* be?

At the beginning of the era of truly capable technologies ("we've got the gear"), we have a unique opportunity to discover/create new frameworks, scenarios, situations, Which disciplines will become crucial? What will actually work? Can we develop new worlds, play in them, and thus learn to prosper in them as they become reality?

Richard Edlund

Thrillrides encompass many techniques - models, motion control photography, animation, live photography, etc. - and ideally culminate in the digital realm. Still, a good story/concept is the key to success and creative attention to preparing an audience for the experience is a must.

Allen Yamashita

Our preoccupation with technology, digital or otherwise, continues to be fundamentally uninteresting to me. I didn't become a filmmaker because I was interested in cameras and lenses, but because this technology accommodated stories of a form and style which, say, writing or dancing did not. I've been making simulator attractions because people are interested in stories which are also experiences. What kind of stories will we be telling tomorrow? They will determine the methodology and therefore, the technology I'll be involved with.

Kevin Biles

Theme park guests expect an experience that is out of the ordinary and something they cannot see, do or experience elsewhere; an experience that puts them in another time, place or world.

CGI has evolved to the degree that it now fits affordably on the palette of techniques we bring to bear in creating theme park experiences. We are less likely to avoid CG imaging because of its former "computer" look, or its cost.

Since it can now easily blend with live action, we are turning to this medium (usually in conjunction with other media) to tell stories and create unique experiences. CGI is becoming a freeing rather than limiting medium. We can keep our focus on audience satisfaction rather than technical limitations of the medium.

Phil Hettema

The "true" theme park experience (which is continually being redefined) requires us to create new applications and interfaces for digital media.

The notion of an all "simulator" or "V.R." theme park is a myth, but digital technology will provide a new level of amazing experiences. Before that can happen, we need to understand the group dynamics which are fundamental to the "themed" experience, and issues of interactive capacity, group interface, and large format display must all be addressed with great creativity.

Brenda Laurel

Brenda Laurel will address issues of interactive collaborative recreation and virtual reality from her unique perspective.

Sherry McKenna

"I want something totally unique—something that's never been done before and, by the way, I want to know how much it's going to cost and how long it's going to take by tomorrow!"

Clients haven't changed but the medium has.

Mario Kamberg

The climate was once dominated by Brut Force and Proprietary Technologies. But now, with the new medium we are back to what film making is all about... creative challenges. Everything in the ride is determined by the stylistic approach of its artisans as the computer is now the slave.

Today's challenges are creative ones, not who's got the most CPU's or a user friendly interface. Particle systems are in everyone's palette... and do you know anyone who can't do a morph?

Now is the time to understand the sinergy of film design and the physical experience. The role of the ride film director/designer becomes more crucial than ever.

We are back in the saddle again: our imaginations are our biggest challenge.

Man vs. Mouse

Chair: Jonathan Luskin

Panelists:
Terri Hansford, MA, PT, CHT, Hand Therapy of San Francisco
Robert E. Markison, M.D, SACS, San Francisco Hand Specialists
Joan Stigliani, Author of *The Computer Users' Guide to Health and Vitality*

Abstract
The purpose of the panel is to raise awareness about Repetitive Strain Injuries (RSI).

RSI, also known as Cumulative Trauma Disorder or overuse syndrome, consists of many different injuries: carpal tunnel syndrome, tendinitis, tynosynovitis, thoracic outlet syndrome, lateral epicondilitis, etc. In 1992, 185,000 office and factory workers suffered RSI. These injuries are now responsible for 1/2 of all occupational illnesses. The panel will describe RSI, other computer related health risks, and how to avoid them. An injured worker, a leading hand surgeon, a physical therapist, and the author of The Computer User' Guide to Health and Vitality, will focus on positive things we can do to improve our health and happiness as computer users.

Topics will include: awareness of the problem, why the "sudden epidemic," form and function of the upper limbs, proper use of limbs, blood circulation, stress, hardware and software ergonomics, and responsibilities of workers, companies, computer manufacturers and government.

The panel will also discuss better computer interfaces for the future, improved work station design, physical therapy and treatment of RSI. There will be an ample questions and answer period allowing for a broad discussion of RSI and other related computer health issues such as eye strain, electromagnetic radiation, and the like.

Multimedia and Interactivity in the Antipodes

Chair:
Lynne Roberts-Goodwin, University of New South Wales

Panelists:
Chris Caines, University of Wollongong
Paula Dawson, University of New South Wales
Adam Lucas, University of New South Wales
Cameron McDonald-Stuart, Apple Australia

Artists, educators and researchers address the development of interactive art and multimedia in Australia, and its relation to similar issues overseas. The panelists present multimedia and interactive artwork from Australia and other countries, discussing issues of availability of these technologies to indigenous peoples, evolving human relationships with interactive multimedia and the role of these new media in cultural, educational and institutional development.

Panel Background
In Australia, interactive art using multimedia technologies is a relatively recent phenomenon. This situation can be attributed to complex cultural, curatorial, aesthetic and technological factors. However, artists, funding bureaucrats, gallery directors and curators in Australia are now beginning to appreciate the importance of interactivity and multimedia, firstly as constituting new formal strategies for critically addressing traditional boundaries between the observer and the artwork, and secondly, as useful tools for opening computing and communications technology to a wider public.

This panel addresses emerging developments in the field of interactivity and multimedia in Australia, mapping out some of the more salient cultural, theoretical and technological factors shaping the current interactive discourse in this country and related patterns and practices in other countries.

The five panelists come from a variety of backgrounds, including art, cultural theory, education and technological development. Each of them has an idiosyncratic perspective on multimedia and interactivity, but a common feature is their commitment to broadening the availability and mode of operation of these new technologies.

Panel Goals and Issues
A fundamentally appealing aspect of interactivity is how the user can navigate the artwork's space of audio-visual information, thereby personally transforming it. The number of permutations in the technological and syntactic means of conveying this information appears to be only limited by the human imagination, so it is perhaps natural that artists have become attracted to these new media with their potential for an expansion of notions of art as merely "object." For an artist working with interactive multimedia, the viewer can become a participant or even co-creator in the artwork and the artwork can become a process of ongoing creativity with a de-centred and de-stratified site of authorship. Communication, participation and creative expansion can all fall together in this process. Enlightenment notions of an individual artistic "genius" are undermined and collectivized. To paraphrase Joseph Beuys, "Anyone can become an artist" by participating in creative dialogues, whether it be with interactive artworks or through electronic networks.

Issues pertaining to the critical reception, funding and production of interactive art and multimedia technologies will be highlighted by the relevant panelists. The emphasis will be placed on issues which are not only specifically relevant to the Australian "Antipodes" at present, but also those which address the common perceptions and reception in global terms of interactivity and multimedia in an arts and cultural context. The presentations will include discussions of artistic and educational uses of CD Rom interactives, electronic networks, and multimedia computing, as well as theories of perception and the use of interactive multimedia by indigenous peoples in Australia and North America.

Chris Caines

The panelist will present his own CD Rom Interactive artwork, titled "The History of Luminous Motion," which is based on a 1992 video artwork dealing with issues of the utopian parallels in the exploration of landscape in technology. The CD will be presented as an example of multimedia interactive art. Through this presentation, the panelist will discuss the ways in which video art and electronic music have been absorbed into interactive multimedia technology, with particular reference to the operation of sound in interactive CD Rom presentations.

The panelist will also give a brief overview of production methodologies relating to the amalgamation of video and interactive multimedia; how this amalgamation transforms language but at the same time creates barriers to artistic expression, and how some artists have made breakthroughs in the artistic potentials of interactive CD Rom.

The panelist will conclude by describing his artistic practice in terms of "the alchemy of converting the linear video work into the fluid interactive rhizomatic CD ROM."

Paula Dawson

This paper will discuss the ways in which multi-dimensional media within contemporary visual arts practice constructs human beings as viewers, respondents or participants. A particular focus will be how the development of 3 Dimensional Spatial Imaging Technology has been shaped through research into patterns of observation (perception theory). Through this development, the relevant properties of humans have become isolated and defined in the extreme. As a result, the means of exchange of stimulus and the precise amount of information needed to generate an image or an environment has become quantifiable.

If we think of how "non-interactive" Renaissance painting constructs the human observer as little more than an "eyeball on a stick," are we in fact less or more? This precision, in relation of the human to the perceived image, speaks primarily of the physiological, sensory connection, whereas the emotional and psychological terrain of virtual interactivity has yet to be defined.

Adam Lucas

The panelist will argue that since the Australian Bicentennial in 1988, the white population's slowly dawning recognition of the continued ill-treatment of the Aboriginal people of this country is finally starting to generate a broad-based cultural dialogue between black and white Australians. New interactive and multimedia technologies have already made a significant contribution to this cultural dialogue.

"Multimedia is Multicultural" is a catch phrase currently being used by computer companies to promote their latest offerings. However, if multiculturalism is to become a reality, rather than just rhetoric, the dominant Western culture must assimilate and come to terms with the knowledge and histories of indigenous peoples throughout the world. This process must involve the active participation of indigenous people in their representations and education of themselves, rather than a continuation of colonialism with members of the dominant culture speaking for and on behalf of the "Other."

Collaborative work between artists and educators from European, non-European and indigenous backgrounds will be discussed as a possible strategy for encouraging this process, with particular reference to projects being undertaken in this area in Canada, the United States and Australia. Issues related to the perception of multimedia/interactive art and the manner in which marginalized groups are integrating new electronic media into their art and cultural practices will be cited, and examples of artwork shown.

Cameron McDonald-Stuart

This paper will present a philosophical, historical and current cultural overview of "Media Integration" in the local and global context of academic and artistic ventures and presentations. Through this overview, the panelist will present and highlight particular examples of New Media Integration in multimedia technologies, citing examples, case studies of projects, research and development and artistic applications of interactivity. The panelist will present and report on the positive and negative aspects of projects and their subsequent outcomes, demonstrating the existence of certain "developmental barriers" that exist in the delivery of the artifacts or products, regardless of their final context and placement. It will be emphasized that definite criteria must be in place at the project's inception in order to fulfill fundamental paradigms of cultural reading. These criteria are skill sets and relevant media issues. The paper and presentation will also cover basic computing and its perceived image in the mass media, in addition to addressing the uses of computing technology in the delivery of education.

Lynne Roberts-Goodwin

The chair will introduce the panel by delivering a short paper encompassing the topics to be discussed by the various panelists, in order to provide a cohesive map of issues and perspectives, including: historical perspectives; cultural considerations; educational paradigms; artistic pursuits; technology transfers and relationships of interactive technologies to present forms of everyday information retrieval i.e. books, video, film, audio-tape, etc.

The chair will also briefly discuss the ways in which people respond to interactive multimedia and assimilate them into their experience through the viewing of artworks, soundworks, performances and broadcast media. This notion of "reception values," which resides with the viewer/respondent, can be paradoxical and problematic due to the nature of the medium and its placement in the gallery, museum, shopping mall, library, expo, etc. The reception/response is obviously dependent on the cultural conditioning of the viewer/respondent, their geographical location and their preconceptions of that technology's potentials. The intention of introducing these issues is to cite the locations at which interactive multimedia is critically assessed, ranging from entertainment, education, artistic production and historical and cultural development.

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The Integrative Use of Computer Graphics in a Medical University

Chair:
Dave Warner, Loma Linda University School of Medicine

Panelists:
A. Douglas Will, Loma Linda University School of Medicine
Jodi Reed, Loma Linda University School of Medicine

The problems in medicine addressed at the Loma Linda University Medical School are problems common to the field of medicine in general. Solutions applied at Loma Linda generalize to the field of medicine, both in study and practice of medicine.

The goal of this panel is two fold. The first goal is to establish a bridge between the computer graphics community and the medical community. The second goal is to demonstrate by example how the integrative use of computer graphics and advanced human computer interface techniques are transforming both the study and practice of medicine. The field of medicine has both the need and the resources to provide the computer graphics industry with new market areas which will aid in the streamlining of the global healthcare system. Examples include innovative applications of educational multimedia, computer graphic visualization of medical data and clinical applications of virtual reality interface technology.

The field of medicine is one of few areas of human endeavor which penetrates almost all aspects of the human experience. Recent developments in human computer interface technology hold great potential in dramatically changing the face of modern medicine.

This panel will present real applications that utilize recently developed computer graphics and interface technologies to assist in the endeavor to continue to enhance health care.

Dave Warner: Clinical applications of advanced interface technologies

Normal people are naturally enabled. They are born with the capacity to interact with the world and willfully manipulate their environments. Disabled people have lost the capacity for such interaction and manipulation through either trauma or disease. Advanced human-computer interface technology that has been developed as natural user interfaces for interaction with virtual reality has immediate application in re-enabling the disabled persons. While virtual reality promises to solve many problems in the future, the immediate application of these advanced interfaces can improve the lives of millions today. At the Loma Linda University Medical Center, we have had many successes in utilizing these technologies. The utility of these devices has already been demonstrated as augmentative communication devices, as environmental controllers, as therapeutic tools in rehabilitation and as tools for quantitative assessment for diagnostic evaluation. Patients who have lost the ability to communicate verbally have successfully used an instrumented glove configured in a gesture to speech mode. Spinal cord injury, stroke and traumatic brain injury patients have virtual reality technology to manipulate virtual objects and practice specific skilled motor tasks. Quadriplegics have used physiological input devices to move objects on the screen with only their eyes and to play virtual instruments merely by contracting face and neck muscles. These are just a few examples of immediate uses for this promising technology that can profoundly improve the quality of life of real people today.

The study and the practice of medicine are intrinsically linked. As information technology becomes more and more relied on in the practice of medicine, so must the study of medicine be adjusted to help prepare the emerging medical professionals for the changes that they are most likely to encounter. This "adjusted" study of medicine must not only modify behavior, but must go beyond and intrinsically change the thinking of the modern health care professional. The integration of computer interaction as a fundamental skill required for the modern healthcare professional will herald a new paradigm for medicine. Technology has only recently reached a result/effort ratio which will propel the medical industry into the 21st century.

A. Douglas Will: Computer graphics and interactive multimedia in the practice of medicine

Today, scientific, economic, technological, social, political and legal forces are converging to form a powerful stimulus for change in health care. The collision of those forces will have an effect that will be as far reaching as the advent of powered flight and as important in its economic and social impact as both World Wars. In 1991, health care jumped a full percentage point, the sharpest one-year increase in three decades. If today's rate of growth continues, health care is projected to reach $16 trillion dollars by 2030, or one-third of the nation's economic output. At the same time 37 million Americans are living today without health insurance coverage.

Health care is a service industry that is intensely dependent on information. Physicians are knowledge workers. Physicians drive most health care costs through the power of their pens. The best way to influence physician behavior and directly impact cost is to provide them with contextually sensitive information in time to impact decisions and improve outcomes. To be successful today, physicians must abandon 19th century industrial aged technologies that they continue to use for maintaining patient's medical records and adopt information tools that place contextually sensitive information at their finger tips.

Knowledge is the unseen phantom driving health care costs. Keeping up with the constant infusion of new knowledge has become intractable. The explosion of knowledge has led to ever increasing specialization resulting in highly inefficient and fractionated care. New tools are needed to acquire knowledge, to access knowledge, and to use knowledge. Three dimensional visualization of anatomic structures must be joined by multidimensional presentation of complex semantic relationships. Animation of molecular processes must replace intellectually opaque verbal descriptions. Perceptualization tools must be developed to enable the knowledge worker to encounter knowledge.

The human computer interface requirements of a real world health care application are demanding. Ease of use and very high performance are coupled to the economic requirement of low cost. Once the fundamental tools have been created to provide the compelling reason for physicians to widely adopt the computerized medical record, new vistas of opportunity will emerge for imaginative visualization of the elaborate "worlds within worlds" of medical knowledge.

Jodi Reed: Issues in the application of advanced educational technologies in medicine

The knowledge explosion of the information age is especially apparent in medicine. Most medical educators have responded by adding content to curriculum. Unfortunately, neither student brain size nor the number of years of medical school has grown. Students respond to this information buildup by studying what they think will help them pass multiple choice exams, resulting in a great deal of frustration, both for students and faculty. Some medical schools have addressed this issue by cutting back content and focusing on process. Problem-based learning, for example, begins a learning session with a clinically-oriented case rather than a barrage of facts. Students are responsible for their learning and are more likely to retain what they've learned when it is learned in context and is learner-directed.

Clinical education, usually the 3rd and 4th years of medical school, is also plagued by the information explosion. Clinicians have turned to increased specialization in response, but medical schools are charged with providing a generalist experience, especially since there is a shortage of lower-paid primary care physicians. Clinical education is often characterized by disorganization and inconsistency, both between and within clerkships. Yet most medical educators would attest that there is an identifiable core of knowledge, skills, and values that should guide curriculum and assessment. How can these issues be addressed?

Systems thinking can help us identify issues and organize solutions, cognitive science can help us create more efficient and meaningful learning situations, and computer science can serve as a tool for both. Intelligent use of computer graphics takes advantage of all three.

This presentation will demonstrate ways we have used computer graphics to address pressing issues in medical education. Obviously, computer graphics alone cannot resolve the administrative organizational challenges, but graphics can be used to increase the efficiency of learning.

Cognitive science has shown us that human working memory can only handle about 7 items at a time. Unless we process these items in some way, they will be forgotten. Much of the utility of good computer courseware lies in its tendency to reduce the load on a learner's working memory. It does this via learner control of pace and detail, reduced time for information access and comparisons, and rich, dynamic, integrated information representation.

We have also learned from cognitive science that facts isolated from meaningful context are easily forgotten. Recent efforts have directed courseware toward case-based simulations that provide meaningful situations and activities for the learner. Timely feedback improves the learner's diagnostic reasoning skills. Use of computer graphics links visual representation with experience, a powerful combination.

Certainly, the future holds increased use of simulation, including use of physiologically-based feedback systems to enhance fidelity and increase the scope of assessment. We are now beginning to use simulation to assess diagnostic and problem-solving skills. Perhaps we will some day use technology to assess a student doctor's communication ability as well.

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Cumulative Index (SIGGRAPH '84 - SIGGRAPH '93)

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"Flowers"
Copyright © 1993 Regents of the University of California
An image of flowers is filtered by a Line Integral Convolution (LIC). The original image was created by pixel replicating a 256 x 256 image to 1024 x 1024. The vector field for the LIC operation was created by taking the gradient of bandlimited noise and rotating each of the gradient vectors 90 degrees. A ramp filter was used in the LIC to simulate brush strokes.

The separations for the front cover image were created through the same digital process used for the recent ACM/Transactions on Graphics special issue on color. The original TIFF file was converted to a device independent color representation and then mapped to a set of printable colors that match, as best as possible, the appearance as the original monitor image. This process provides better color fidelity and more image detail than printing and rescanning the picture. See the introduction to the October 1992 issue of TOG for more information about the process.
Reference: *"Imaging Vector Fields Using Line Integral Convolution,"* Brian Cabral and Leith (Casey) Leedom, p. 266

Title image

"Room with Books"
Copyright © 1993, Program of Computer Graphics, Cornell University
An architectural interior rendered using a combination of hierarchical radiosity and discontinuity meshing. The interior was modeled by Matt Hyatt and rendered by Dani Lischinski and Filippo Tampieri.
Reference: *"Combining Hierarchical Radiosity and Discontinuity Meshing,"* Dani Lischinski, Filippo Tampieri, Donald P. Greenberg, p 207

Back cover, top left

"Traffic Jam to Point Reyes"
Copyright © 1993, Scott R. Nelson and Michael F. Deering, Sun Microsystems Computer Corporation
Inspired by Rob Cook's 1983 image "Road to Point Reyes," this image was rendered on a SPARCstation 10 ZX as a single scene using hardware lighting and Z-buffer. Eight-pass stochastic sampling was used to antialias the scene, which contains more than 2.3 million triangles. Models are courtesy of Viewpoint Animation Engineering.
Reference: *"Leo: A System for Cost Effective 3D Shaded Graphics,"* Michael F. Deering, Scott R. Nelson, p. 108

Back cover, top right

"Interior of a Temple"
Coypright © 1992, 1993 Harold R. Zatz and Cornell University
This image was computed in parallel on an Apollo DN10000, five HP 9000/720's, and five DECstation 3000's. It shows the interior of a temple composed of 607 parametrically defined surfaces. Using the Galerkin method, radiosity values were determined as polynomial functions over these surfaces, eliminating any need for meshing or tessellation. The image was ray-traced directly from the radiosity solution, without interpolation.
Reference: *"Galerkin Radiosity: A Higher Order Solution Method for Global Illumination,"* Harold R. Zatz, p. 220

Back cover, middle left

"Development of *Hieracium umbellatum*"
Copyright © 1992, Przemyslaw Prusinkiewicz, Mark Hammel, and Eric Mjolsness
The head of *Hieracium umbellatum* undergoes a sequence of transformations during its development from a bud to a flower to a fruit. The figure combines selected frames from an animation of this process. The model has been expressed using the formalism of differential Lindenmayer systems. The image was created on a Silicon Graphics 4D/310 workstation.
Reference: *"Animation of Plant Development,"* Przemyslaw Prusinkiewicz, Mark S. Hammell, Eric Mjolsness, p. 359

Back cover, middle right

"Hyperbolic Space"
Copyright © 1993, The Geometry Center, University of Minnesota
Modeling and rendering by Charlie Gunn using Mathematica™ and Renderman™
This image shows a tessellation of hyperbolic space by regular right-angled dodecahedron. It arises in the investigation of the geometry of the complement of the three linked circles known as the Borromean rings and is featured in the mathematical animation "Not Knot."
Reference: *"Discrete Groups and Visualization of Three-Dimensional Manifolds,"* Charlie Gunn, p. 261

Back cover, bottom left

"The Earth taking into Account Atmosphere"
Copyright © 1993, Fukuyama University and Hiroshima Prefectural University
Artists: Tomoyuki Nishita, Takao Sirai, Katsumi Tadamura, Eihachiro Nakamae
This image was created on an IRIS Indigo Elan using software by the authors. The intention of the image is application to space flight simulators and the simulation of surveys of the earth; displaying the earth including the surface of the sea viewed from outer space taking into account particles (air molecules and aerosols) in the atmosphere and water molecules in the sea.
Reference: *"Display of The Earth Taking into Account Atmospheric Scattering,"* Tomoyuki Nishita, Takao Sirai, Katsumi Tadamura, Eichahiro Nakamae, p. 181

Back cover, bottom right

"Surface of Ion-Bombarded Graphite"
Copyright © 1992, The University of North Carolina at Chapel Hill
Created by Russell M. Taylor II and R. Stanley Williams with custom software on the Pixel-Planes 5
Shaded STM image of ion-bombarded graphite sample. This image shows tip scratches on the lower left part of the sample and ripples in the upper right corner caused by sheets of graphite pushing up out of the surface. The surface is colored according to height, with redder areas at higher elevations.
Reference: *"The Nanomanipulator: A Virtual-Reality Interface for a Scanning Tunneling Microscope,"* Russell M. Taylor II, Warren Robinett, Vernon L. Chi, Frederick P. Brooks Jr., William V. Wright, R. Stanley Williams, Eric J. Snyder, p. 132

Notes

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Your mail will be scanned by an automated mail responder which will try to respond to keywords in your subject line and message body with SIGGRAPH resources of interest to you. If you do not know where to begin a search, simply forward an empty message with the subject line "help." A general directory assistance message will be returned immediately to you.

If you want to reach someone whose name you know, address the mail as surname@siggraph.org where surname is replaced by the person's surname and, again, capitalization is not important. For example, to reach Adele Newton, address mail to newton@siggraph.org. In case there is more than one person with a given surname, use the first initial followed by the surname. For example, to reach Judith R. Brown, address mail to jbrown@siggraph.org; to reach Maxine Brown, use mbrown@siggraph.org.

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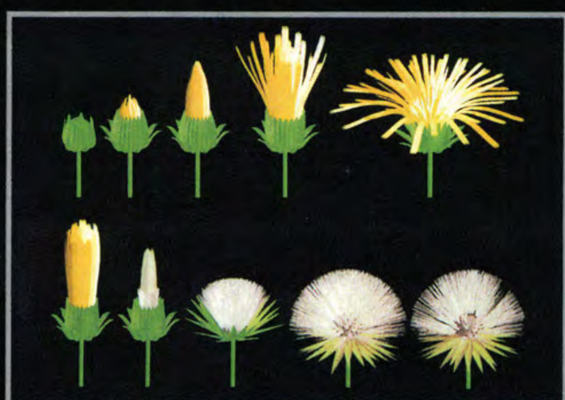
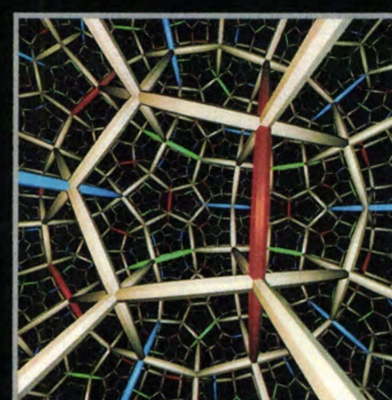

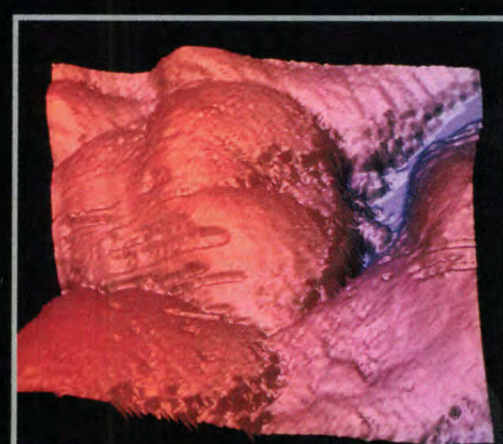

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