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the surface, sending jets of gas and dust into space, as we have seen emanating from Saturn's moon Enceladus and numerous comets. Ices exposed on the cold surfaces of outer planetary moons interact with the local space environment, as the incident solar ultraviolet light and charged particles from deep space and trapped in the parent planet's magnetosphere cause chemical changes in the ice and its evaporation into space by sputtering. Although these chemical changes occur at the molecular and even the atomic level, remote-sensing instruments on Earth and on passing spacecraft can detect them directly by optical (ultraviolet through infrared wavelengths) spectroscopy and by measurements from flybys high above the surface.

The origin of carbon dioxide is less clear, and requires either that CO_2 is native to Rhea's icy inventory, or that it forms at the surface from the released O_2 acting on carbon-rich grains. Such grains may be native to Rhea or entrained in its ice, but a more likely source is the carbonaceous micrometeorites that continuously dust the solid bodies of the solar system, including Earth.

In the tenuous O_2 atmosphere of Rhea, molecules rarely collide with one another, such that the rate of escape into space approximates the rate of ejection from the surface. Therefore, in the current epoch, the atmosphere is probably not increasing appreciably in density and surface pressure. However, Teolis *et al*. find that the rate of O_2 generation in the ice exceeds the rate of ejection from it, leading to the buildup of an oxygen reservoir. The episodic or long-term release of this stored oxygen could increase the total atmospheric density, but it would still be considered tenuous.

The presence of an oxygen-rich atmosphere of entirely radiolytic (photodriven) origin raises the question of using the detection of oxygen on an extrasolar planet as a criterion indicating the occurrence of life. The first detection of an oxygen-rich atmosphere on an extrasolar planet is likely to be accomplished by spectroscopy, which will require a somewhat denser atmosphere than Rhea currently has. It is notable, however, that emission of atomic oxygen in the tenuous atmospheres of Jupiter's moons Europa and Ganymede was detected by ultraviolet spectroscopy with the Hubble Space Telescope (*5*) and similarly in an extrasolar planet atmosphere (*6*). Additional laboratory and theoretical studies of O_2 production in ice by interaction with the nearby space environment and the development of a dense atmosphere should further clarify the feasibility of using this particular criterion, often cited as a hopeful sign of life in a remote planetary system (*7*).

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COMPUTER SCIENCE

Computational Physics in Film

Numerical modeling of how objects and fluids move, collide, and break up underlies spellbinding video animations.

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Computer simulation of solid and fluid dynamics underlies many visual effects seen in films produced during the past decade. This approach not only is less expensive than filming live action but also can avoid putting actors and crews in dangerous settings and can allow visualization of the impossible. Compared with more traditional animation methods that rely chiefly on artists' efforts, numerical solutions to the equations of physics allow computers to calculate realistic motion, such of that of smoke, fire, explosions, water, rubble, clothing, hair, muscles, and skin. Algorithmic advances now afford artists a higher-level, more efficient role in guiding the physics as they produce animation. We provide an overview here of current challenges in physics-based animation.

The movement and collisions of rigid bodies have long been the mainstay of physics-based animation, but modeling and integrating frictional contact remains a serious challenge. Structured stacks of blocks, highly nonconvex geometry, and delicate balances between pressure and friction all can pose torture tests for numerical methods that must exactly balance forces to keep these assemblies stable. Kaufman *et al*. (*1*) discuss new methods that use alternating projections (a way to calculate where interactions occur) to solve a constrained optimization formulation of contact.

Some objects, such as hair and clothing, are naturally deformable, which complicates the collision problem. In hair simulation, modeling the contacts between individual hairs creates a problem of computational scale. Resolving all of the collisions between the 100,000 hairs on a human head overwhelms brute-force methods. McAdams *et al*. (*2*) have taken a multiscale approach by treating hair as a continuum fluid, rather than discrete strands. This approach resolves the motion of the hair as a whole by averaging the motion into a continuous vector field, but truly accurate vector-field equations have yet to be derived. Kaldor *et al*. (*3*) have taken the opposite route in clothing simulation. Rather than use models that homogenize the two-dimensional (2D) surface of clothing, they perform a full simulation of every loop and twist in the yarn of knitwear and create subtle behaviors that simpler methods cannot reproduce. However, densely woven fabrics still require more efficient modeling as isometric surfaces, ones that bend but do not stretch or shear. English and Bridson (*4*) recently resolved the "locking" problem plaguing earlier efforts in which isometry constraints inadvertently prevent the natural bending. Paradoxically, their solution involves allowing holes to open up in the cloth between mesh triangles (the numerical regions into which the surface is decomposed). This finding poses interesting questions in discontinuous geometry, in that the mapping from surface parameters is neither continuous nor differentiable.

Volumetric elasticity—handling fully 3D deformation—is used in biomechanical models of the flesh of virtual creatures (*5*). Studios are rapidly increasing the anatomical detail of their models, from the complexities of muscles and tendons to delicate wrinkles in the skin. The amount of detail in the surface as well as the structures underneath the skin (muscles, tendons, bones, and other organs),

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and the precise calculation of force response for different materials, all contribute to the ongoing challenge of controlling the motion of characters while making it appear that simulated muscles are doing the work.

Objects not only move, they also break. Research efforts in depicting fracture mechanics began with O'Brien and Hodgins's work (*6*) using remeshing, which improves the geometric fidelity where surfaces break by changing the mesh in that region. More recent techniques embed crack geometry in finite elements models of the mechanics (*7*, *8*). These simulations are still difficult to control and have yet to truly break into film production.

Some of the most spectacular examples of physics in film involve fluids, where nonlinearities in the underlying Navier-Stokes equations that describe fluid motion lead to accumulation of remarkable geometric complexity. A recent trend for depicting liquids has been the emergence of mesh-based surface tracking. In a preliminary attempt to follow the details of a water surface as closely as possible, Brochu *et al*. (*9*), inspired by approaches for cloth collision processing, developed a method that matches the degrees of freedom in the simulation to the geometry of the deforming surface mesh, rather than the other way around. However, the difficulties involved in making this approach truly robust are still daunting; meshes in three dimensions find endless ways to cause numerical and combinatorial troubles.

Horvath and Geiger (*10*) have probably achieved the greatest level of detail yet in fire and smoke with a two-level approach. The hybrid particle-grid method (fluid-implicit particle, or FLIP) (*11*) provides a high-quality (albeit relatively low resolution) 3D simulation. They use it to guide extremely high-resolution simulations on 2D slices through the volume (oriented to the camera), running in parallel on commodity graphics processing unit (GPU) hardware. This idea of getting the bulk motion from fast, low-resolution simulations and then adding localized detail with secondary simulation is being pursued by many groups, although properly accounting for dynamics within a grid element at low resolutions remains a major hurdle.

The problem of scale in general looms large (and small). Consider a ship on a rough sea; the figure shows fairly convincing detail that is achievable on a single workstation today [a full movie clip is available, see (*12*); a compressed version is available at (*13*)]. This simulation still falls far short of a shot encompassing stormy waves to the horizon as well as small scales down to the tiny droplets breaking up on the rigging. Brute-force methods of today would require orders of magnitude more computing resources than are available.

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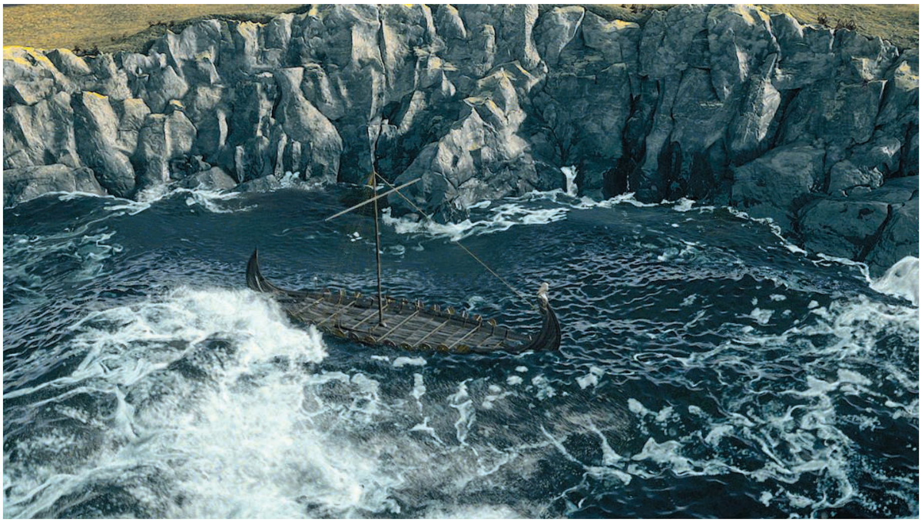

Realistic simulations. A simulated ship upon a simulated ocean. Here, the film industry's Naiad software is used to evolve the incompressible Navier-Stokes equations for the water, strongly coupled with the rigid-body dynamics of the longboat, with additional phenomenological simulation of foam and spray.

The other performance challenge is increasing speed at the simulation resolutions currently in use. Studios can cope with simulations running overnight, but such time scales do not allow much scope for iterative refinement. When film-quality simulations can run at real-time rates, remarkably more effective artist interaction is possible—not just more design cycles but also experimentation with continuous feedback. With more general simulations emerging that fully couple all of the solid and fluid dynamics mentioned above, we are already beginning to see the advent of "virtual practical effects." Artists can use their natural intuition about how physics works to build virtual devices to control the virtual world of a shot, rather than awkwardly manipulating parameters in equations.

The quality of physics-based animation methods is not simple to evaluate. Ultimately, success is judged by the director, and the worth of the underlying algorithms can be judged by the users based on how well it helps them do their jobs. However, given the time and effort involved in using a new method in production, and the difficulty of creating objective, quantitative metrics, researchers need something better to analyze their efforts.

Classic means of evaluating algorithms, such as convergence rates for iterative schemes, have limited use. Qualitatively good results (ones that convince audiences) are usually obtained well before a model simulation converges. Psychophysical results in video compression, for example, also suggest that the mathematically convenient norms commonly used in numerical analysis are not a good match for human-oriented evaluation. Moreover, assessing the errors in underlying models on which algorithms are based is a particular challenge for film.

Unlike traditional science, reality does not necessarily provide a ground truth against which film models can be compared. Film production on a set already demands something enhanced beyond reality. Tackling the problem of objective and useful evaluation will likely demand cross-disciplinary efforts in understanding the human perception of complex dynamics. In the short term, success can continue to be judged by increasing calls for "lights, camera, simulation."

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